

Research Report
UKTRP-83-17

HIGHWAY SKID RESISTANCE

by

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in cooperation with the

Transportation Cabinet
Commonwealth of Kentucky

and the

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16. Abstract The physics of friction and traction are reviewed. Hypotheses are presented. Use of a scanning electron microscope to detect and identify polishing aggregate is presented. Size reduction (crushing) produces greater concentrations of sharp edges, reducing flat and plane surfaces not otherwise contributing to traction. Surface permeability and drainage through macrotexture was evaluated by an air-percussive device. An air-efflux device was contrived for evaluating hydroplaning potential and for evaluating open-graded surface courses. In-filling has been observed where road debris is abundant. Grippers and sharpness are needed for wet traction. Drainage is needed to lower hydroplaning potentials. Sand-sizes optimize the concentration of grippers; open-graded chip-sized surfaces maximize drainage and dissipation of pressure under tires.			
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EXECUTIVE SUMMARY

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HIGHWAY SKID RESISTANCE

To safeguard highways against slipperiness, one must understand the mechanics of traction in order to design remedies and to optimize practices. One must visualize a due portion of "grippers" in the pavement surface and the necessity of minimizing the smooth or polished areas that may be easily lubricated with water. Flat surfaces together with a high concentration of sharp edges (small size sands) may suffice, but sharp asperities are probably preferable. These factors control traction when the pavement is wet. A waffled texture cups water under the tire, whereas the tire should function somewhat as a rolling squeegee. Only adherent water should remain under the tread. Hydroplaning pressures rise when the water is deep and cannot escape fast enough. A back pressure begins at the front of the tire and causes liftoff. At the onset of liftoff, the back pressure approaches tire inflation pressure. Liftoff progresses rearward as depth increases and as speed increases. At total liftoff, the wheel stops rotating (spindown); and there is no traction.

Surface drainage is an important factor. Drainage is enhanced by the cross slope of the pavement. During a heavy downpour, the depth of water may easily exceed one-quarter inch. To avoid hydroplaning, traffic must decrease speed. Time to run off is important. Textured and grooved pavements presumably enhance drainage and the emergence of peaks in the texture. Internal drainage is achieved by using open-graded surface courses.

Hydroplaning potential may be measured (at least compared) by water-efflux observations and by texture measurements. Here, a simple air-efflux device is described and presented along with on-road measurements.

It is concluded that examination of chips from pavements by SEM reveals tendencies of aggregates to round and polish. Air-efflux tests suffice to generally confirm that an open-graded surface is open or has been closed by in-filling of voids with road debris. Usually the test merely confirms visual observations.

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INTRODUCTION

A vehicle is presumably under the control of the driver (if he or she is alert and well) until the onset of slippage or until airborne. A driver may regain control after slippage ceases and following a severe upward bounce. A momentary impulse of braking may induce slippage. A dip or bump in the road may cause an automobile to bottom out and to rebound. The tractive forces generated by driving maneuvers are limited, of course, by the skid resistance of the pavement. A braking force of 0.5 g is sufficient to unseat an unrestrained child or an unwary, unbelted passenger. Many pavements, when wet, have a tractive (skid) resistance in the order of 0.4 to 0.5 g (equivalent to SN = 40 and SN = 50). Only rarely and only in cases of emergency and panic will a driver require such forceful maneuvering. On the other hand, if traction is limited to 0.2 to 0.3 g (when wet), normal maneuvers may not be executed without risk of slippage. Resistance to skidding and slippage is related to texture of the pavement and to tire tread.

For convenience, researchers use the term macrotexture when alluding to hydroplaning and skiing speeds. They use microtexture to allude to lubrication of the interface between the tire and pavement and the loss of frictional resistance. The ranges and boundaries are not well defined. Macrotexture surely encompasses knobby and pebbly surfaces.

Standing water, sheet flow (due to grade and cross slope), dew, cupped water (micro), spillages, etc., are causes of slipperiness. Oil slicks and dew combine to form an insidious peril. Icing, especially glazing, has caused epidemics of accidents.

The attributes of a pavement providing maximum safety include good drainage (runoff and efflux through grooves in the surface or through

internal pores -- the latter at the risk of damage due to freezing) and persisting, non-polishing grippers and cutters in the micro- or middle-range dimensions of asperities. The asperities must indent the tire rubber to resist sliding, even when dry. Rutting and wear in wheel paths cause channelization of runoff (depth of water increases downgrade). Warping, due to earth subsidence and superelevation at curves, especially on multilane highways, may cause excess accumulations and increases of water depth unless in-pavement interceptor drains are provided. Longitudinal grooving causes fish-tailing of some vehicles and loss of driver control. Some water is retained and cupped.

All pavements provide good traction when dry. Sand spillages or other small granular material may create a roller-bearing effect and cause loss of driver control. Spillages of deliquescent chemicals, such as calcium chloride, and of engine oils and antifreezes are very hazardous. Soil and mud, wet leaves, polyethylene sheeting, wet newspapers, etc., are likely to induce slippage.

Skid resistance may be associated empirically and phenomenologically with attributes of surfaces (polishing; wear; macro- and microtextures; height, shape, and sharpness of asperities; distribution and concentration of asperities; etc.) and with physical parameters or attributes of aggregates (hardness, fracture modes, cleavage, porosity, etc.). Shear forces in the tire equate to shear forces in the pavement. Peak resistance is achieved when the tread rubber is strained to its limit. Rubber may be gouged, torn and melted; heat and sparks are generated at the interface.

A multiplicity of laboratory machines has been devised to model, simulate, intensify, and accelerate the effects of traffic on a

pavement. Field-testing remains the method of proof-testing all theories and models and empiricisms. Much remains to be learned; surface textures, polishing, coarse wear, and attrition are being investigated. Scanning electron micrography (SEM) offers promise for discovery and explanation of phenomena. Studies are in progress. A long-time study on "Aggregate Shape and Skid Resistance" has been completed (1). Preliminary looks at SEM's of chips from the wheel paths of pavements have been completed.

Relationships between skid resistance and wet-weather accident frequencies have been derived (2, 3). Criteria have been advanced and adopted in Kentucky for specifying surfaces for skid resistance (4). Criteria have been advanced for deslicking or otherwise treating known or reported sections of slippery roads in Kentucky (5).

PHYSICS OF SKID RESISTANCE

FIRST PRINCIPLES

The kinetics and dynamics of skidding and of acceleration and deceleration are relatable to elementary principles of physics, as follows:

$$\text{Force of Friction} = fW \quad 1$$

and

$$\text{Force of Inertial Body} = ma = Wa/g \quad 2$$

in which

f = coefficient of friction,

W = weight,

m = mass,

a = acceleration in direction considered, and

g = acceleration of gravity.

Balancing (equating) forces gives the following:

$$fW = Wa/g, \text{ or } f = a/g = g's. \quad 3$$

Equating energies gives

$$fWS = Wv^2/2g \quad 4$$

and

$$f = v^2/2gS = v^2/30 S \quad 5$$

when V is in miles per hour and S is in feet. S is the skidding stopping distance, and V is the velocity at the beginning of skidding. As an example, a vehicle traveling 60 mph would skid 120 feet if $f = 1$. Note that when $f = 1$, $a = g$; and the horizontal stopping distance is the same as the height the vehicle would hurtle if the road turned upward.

WHEEL AND BODY BOUNCE

Tire traction or friction force varies with the vertical force of the tire on the pavement. Tires, axles, and bodies undergo vertical motion (or bounce) as they travel; this motion arises from pavement roughness, wheel imbalance, wind, etc. Wheel bounce indicates the force on the pavement may be greater or lesser than the static load. Yaw, tilting, or swerving of the vehicle causes load transfers among wheels and unbalances forces of traction. To measure f accurately, the vertical force must be monitored; the instantaneous value of

Force_(horizontal)/Force_(vertical) = f. Bounce frequency (f_n) in cycles per second (cps) of a sprung body is

$$f_n = 3.13/\sqrt{d}, \quad 6$$

in which d = static deflection (in inches) of tire or load springs.

The bounce frequency of the rear wheels and axle depends on the static deflection of the tires. If d = 0.25 inch, $f_n = 6.26$ cps. If the deflection of the load springs is 4 inches, the bounce of the body would be 1.57 cps. Excess kinetic energy induced by bouncing dissipates in an oscillatory motion that is damped by friction in bearings and springs and by shock absorbers.

SPRAY AND TRAJECTORY: HYDROPLANING

Horne's formula (6, 7) for total hydroplaning is

$$V_{crit} = 10.35\sqrt{P_i},$$

in which V_{crit} is the critical velocity in mph and P_i is the tire inflation pressure in pounds per square inch. When P_i is 28 psi, V_{crit} is 54.8 mph (80.4 ft/sec). Partial hydroplaning and partial loss of traction occurs at lower velocities.

Creation of spray by a tire (Figures 1 and 2) involves the transfer of momentum to the water. The velocity of the water may be close to or be slightly less than the forward speed of the tire. Equating kinetic energy ($KE = mv^2/2 = Wv^2/2g$) and potential energy ($PE = Wh$) yields $v^2 = 2gh$; and $h = v^2/2g$ is the classical expression for velocity head in hydraulics. The pressure at the bottom of a column of water 64.62 feet in height is 28 psi (equal to p_i). Equating this to velocity head,

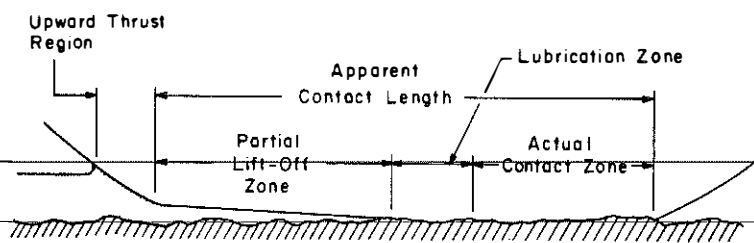
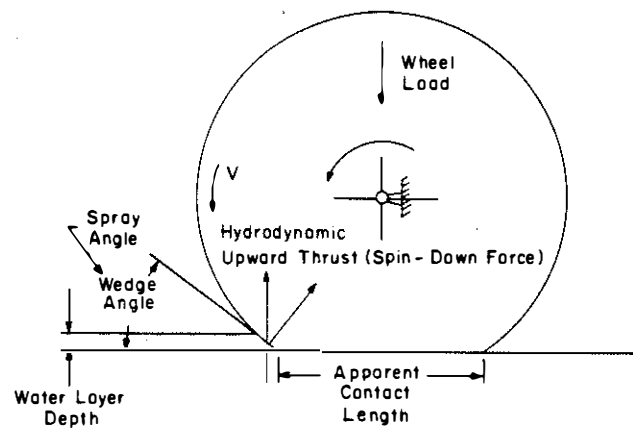


Figure 1. Hypothesized Three-Zone, Three-Stage Concept of Hydroplaning (Gough, 1959) (7).



Figure 2. Road Spray and Inadequate Surface Drainage, US 60 West of Lexington; Section Reconstructed (9-27-76).

$$v^2 = 2 \times 32 \times 64.62,$$

or

$$V = 64.3 \text{ ft/sec.}$$

This would be the exit velocity of a spray induced by a tire pressure of 28 psi. The maximum rise of spray exiting at an angle θ is $h = v^2/2g \sin^2\theta$.

If all of the water in a tire print 1/8 inch deep by 4.5 inches in length and 6.5 inches in width were sprayed by a tire inflated to 32 psi, the maximum exit velocity would be 64.3 ft/sec; the least path from the center would be 2.25 inches; and the escape time would be 0.0055 sec ($at^2/2 = 2.25$). Using $F = ma$, for comparison, $F = Wa/g$, or $W = 0.125 \times 4.5 \times 6.5 \times (62.4/1728) = 0.132$ lbs per tire print and $F = (0.132/32) \times (68.75/0.0055) = 51.6$ lbs. On the other hand, the time to lay down a tire print 4.5 inches in length at 54.8 mph (80.4 ft/sec) is 0.00467 sec and $F = 60.8$ lbs. Therefore, $F = ma$ applied to spray does not suffice in a very significant way to account for total hydroplaning back pressure unless the water is very deep. For this force to approach the weight of the wheel of an automobile (here taken to be 896 lbs), 15 to 20 times more water would have to be sprayed. This would be equivalent to a 2- or 2.5-inch depth of water. Liftoff occurs first at the leading end (toe) of the footprint and progresses to the rear (heel) at higher and higher speeds. The pressure, therefore, is not uniformly distributed under the tire or else the tire is preferentially indented at the front. Figure 1 depicts a wedge of water at the toe of the footprint. For 50 percent liftoff, the water would have to be only half as deep. Loss of traction would be 50 percent or greater ($P_h/P_i =$

0.50).

Peaking occurs about midway through the footprint of the tire (Figure 3). The dwell time of a tire print ranges from about 0.008 sec at 60 mph to about 0.025 sec at 20 mph.

SHEAR STRAIN IN TREAD RUBBER

Tread rubber in contact with the pavement undergoes tangential strain (shear) in some proportion to the tractive force. Others have noted that the tire print is displaced rearward during braking. Surely, the rubber strains considerably; this strain and recoil probably account for the squeal of tires on dry pavements. Thick treads would stretch or shear more than thin treads. In a locked-wheel slide, the same tire print is being stretched and torn continuously. However, if the wheel is merely braked, the velocity of the vehicle at any instant must be the sum of the true rolling velocity ($\text{rps} \times \text{circumference of wheel}$), the true slip velocity (if any), and that portion attributable to stretching in the tread. If the average or effective shear is 0.10, this component of velocity is proportional to thickness of tread and to rps of the wheel and may be stated as a percentage of vehicle velocity only if there is no slip. For 0.5-inch tread thickness, it would be 5 percent of the vehicle velocity. In any case, it seems possible that the peak coefficient of friction ($\text{PSN}/100$) is also decomposable into components. The tractive resistance of the tire tread may be stated as the product of shear strain in the rubber, shear modulus of the rubber, and the real contact area. This product divided by the normal force W (here 896 lbs) yields a coefficient of friction. The real contact area on a dry fine-textured surface is considered here to be about 80 percent of the apparent area; the apparent area is approximated by W/P_1 , where P_1 is

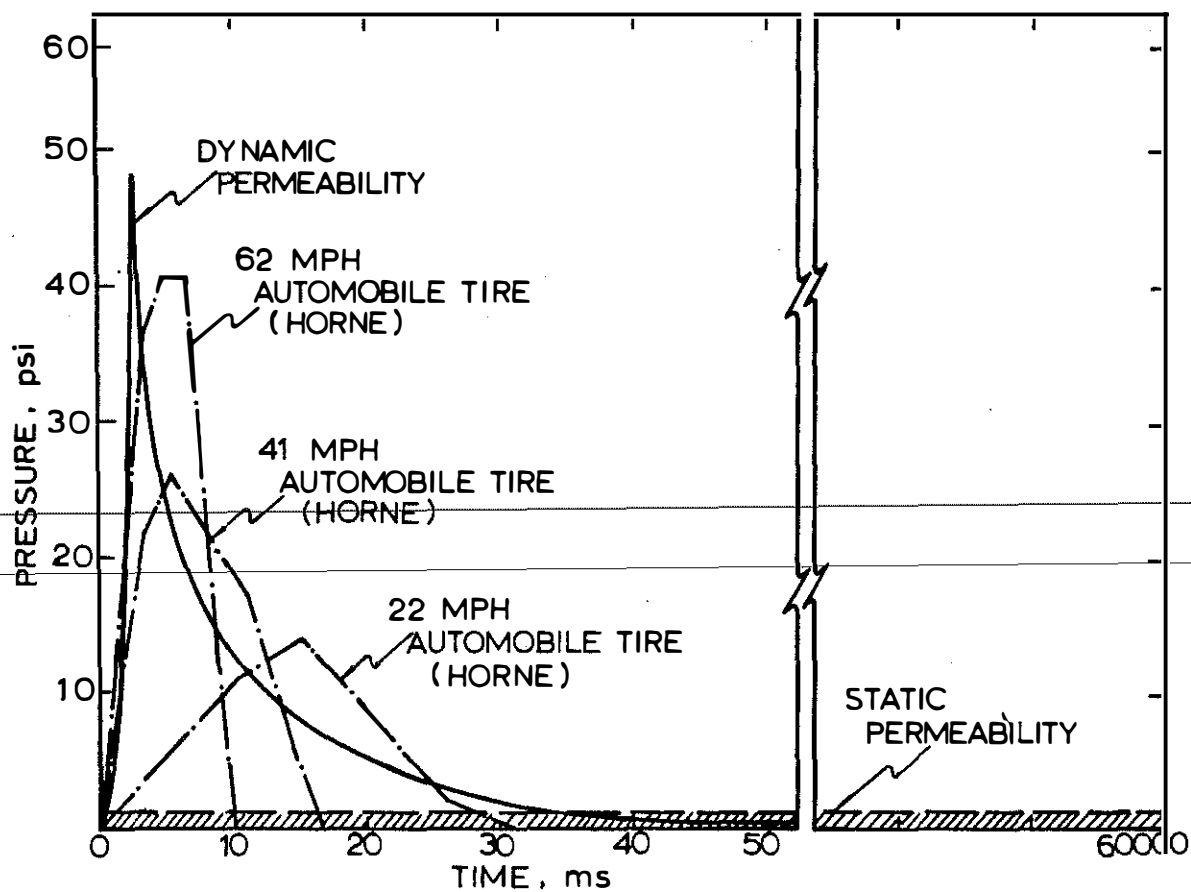


Figure 3. Horne's (7) Hydrodynamic Pressures under an Automobile Tire at Three Speeds and Hutchinson, Kao, and Pendley's (16) Dynamic Permeability Pressure Peak.

the tire pressure. Grooves and sipes in the tread pattern diminish the contact area but increase the contact pressure. The equation hypothesized corrects for hydrodynamic or air pressure (P_h) and smoothness (A_s) of the pavement surface, as follows:

$$\text{Peak Friction (or PSN/100)} = f.$$

The force of friction is

$$F = fW = (\epsilon_s \times E_s \times 0.8 W/P_i) (1 - A_s/A_t) (1 - P_h/P_i) \quad 8$$

in which ϵ_s = shear strain = 0.115 in./in. (maximum deduced for $f = 1$),

E_s = 348 lbs/in.² (handbook value of shear modulus of tread rubber),

A_s = smooth portion of tire print (area void of grippers and subject to lubrication),

A_t = gross or apparent area of tire print = W/P_i , and

PSN = peak skid number (occurs prior to slippage).

The expression for dry friction is

$$f = \epsilon_s \times E_s \times 0.8/P_i.$$

Dry friction is always assumed to be 1.0, and therefore $F = W$. All

other factors are friction-reducing factors. First, let $P_h = 0$, $P_i = 32$

psi, $W = 896$ lbs (wheel load), and $A_s = 0$:

$$\text{PSN/100} = f = 0.115 \times 348 \times (0.8/P_i) = 1.$$

Letting $P_h = 16$ psi and $A_s = 14.0$ in.²:

$$\begin{aligned} \text{PSN/100} = f &= 348 \times 0.115 \times (0.8/32)(1 - 14.0/28)(1 - 16/32) \\ &= 0.25 \end{aligned}$$

The limiting value of shear strains, above, was deduced for $f = 1$.

Assuming a tread thickness of 1/8 inch, the effect on vehicle velocity, assuming no slip, is $1/8 \times 0.115$, or 1.44 percent; one-half inch of tread would account for 5.75 percent of the velocity. This hypothesis implies that for peak friction to develop any contact between tread rubber and a dry pavement surface induces maximum shear in the tread rubber in the contact area. All traction is lost when $P_h = P_i$. Wet friction is lubricated slippage. The factor A_s/A_t expresses the fractional part of the tire footprint smooth enough to be lubricated by water not squeezed from the tire-pavement interface. This reduction applies to the area that has not been lifted off by P_h .

To effect maximum deceleration, the tread rubber must be stretched to its limit; only then is the tractive force at its maximum. Loss of friction during slip is due to melting of rubber and to lubrication. There is no adhesive component of force unless melting occurs and unless skid marks (laydown of rubber) are evident. Contact or bearing pressures at the peaks of sharp asperities undoubtedly far exceed tire inflation pressure. Surely, those high pressure points function as grippers and cutters penetrating through water films and providing traction.

A driver who pumps the brakes to achieve peak traction may travel farther than when braking steadily or in a locked-wheel skidding mode.

A complete skidding-stop excursion is shown in Figure 4. Deceleration was measured in g's. Peak deceleration occurred just before slippage. Note also the backlash in the tires and car body after stopping. Figure 5 shows a recording of a lock-up and steady-state skid excursion by braked wheel on a skid-test trailer. Peaking is very evident there too.

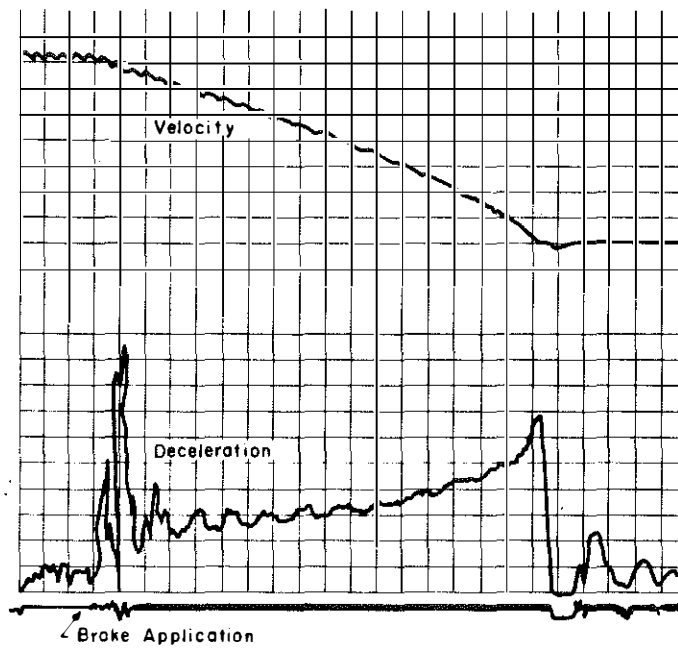


Figure 4. Decelerations in a Skidding Stop. Deceleration in g's is equal to the coefficient of friction. Note logarithmic decrement after stopping. This is due to oscillation of the vehicle and dissipation of energy in the body. There is also a backlash due to strain in the tire tread.

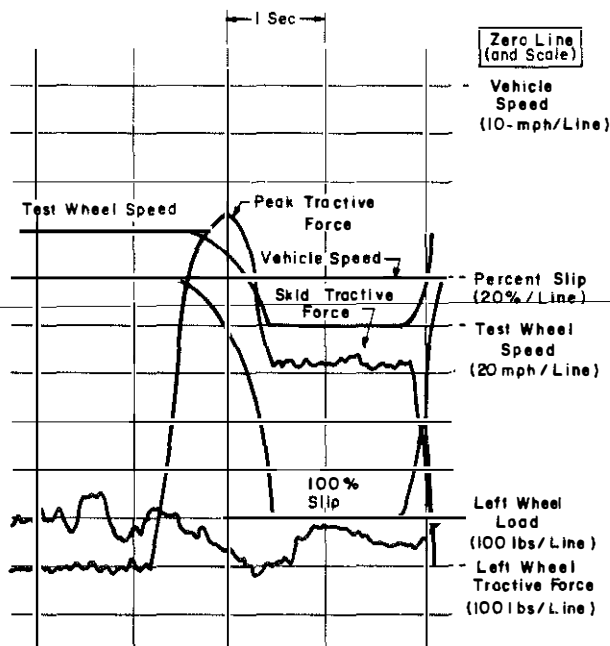


Figure 5. Lock-Up and Steady-State Skid Test.

LUBRICATION

Tires are somewhat like a roller squeegee. Tread grooves leave water on the pavement, but the proud parts of tread tend to displace all free or loose water. Even so, and apart from hydroplaning water pressures, some adherent water remains and is sufficient to lubricate the pavement-tire interface. This condition yields wet friction coefficients. Put a drop of water on a piece of glass and rub it with a pencil eraser; then try a dry eraser on a dry area of the glass. A basic consideration in lubrication is film strength of the liquid, whether it is water or other liquids. Water has very low film strength compared to oils. Pressure on asperities increases with sharpness at the apex. Fretting in metal bearings occurs because of failure of the lubricant (oil) at high contact pressure points. When the lubricant fails, pressure points weld together. The weaker metal pulls loose and is, thereby, transferred to the stronger side. Sharply pointed asperities or sharply edged facets in the tire print serve as grippers and cutters that indent the tread rubber and break the water film. The occurrence (concentration) of peaks and sharp edges increases as particle size of the aggregate decreases. However, the height of asperities will decrease. Whether or not sharp points are superior to sharp edges must be considered; surely, the limit on size does not exclude fine sands.

STOPPING DISTANCE

Skid resistance measured with a trailer-type tester reflects the frictional properties of the surface at specific velocities. The problem of relating this information to stopping arises because the skid coefficient increases as the speed decreases. Each surface exhibits its

$$+((V_n^2 - V_0^2)/30f(V_n) - 0)$$

13

in which $f_{(V_a-V_b)}$, $f_{(V_b-V_c)}$, etc., are the measured coefficients of friction at midpoints between velocities V_a-V_b , V_b-V_c , etc. This equation is equally applicable when using coefficients of friction measured over increments of velocity in a skidding automobile (not necessarily to a dead stop).

Using Rizenbergs and Ward's data (9), a comparison was made between the mean skid distances for four sites and the distances computed. The velocity at wheel lock was about 40 mph and the velocity increments were 10 mph, i.e., 40 to 30 mph, 30 to 20 mph, etc. The results are summarized in Table 1. Obviously, the differences between the measured and calculated skid distances are negligible, and the practical implications of such computations are apparent. Quite possibly, coefficients of friction for wider velocity increments could be used to achieve good results. The skid distance determination could be further simplified by substituting S_x for the computed skid distance in the last 10-mph increment, since skid measurements at low velocities are difficult to conduct. The magnitude of S_x could be based upon coefficients of friction at the higher velocities. The contribution of S_x to the total skid distance S_t is quite small. The equation would become

$$S_t = \sum S(V_a - V_b) + S(V_b - V_c) \dots + S(V_n - 10) + S_x. \quad 14$$

TABLE 1. SKID DISTANCES (feet)

=====				
SITE	MEASURED	CALCULATED (EQ 14)	PERCENT ERROR	AVG VELOCITY AT WHEEL LOCK

2	126.2	126.8	0.5	39.4
3	95.0	96.3	1.8	39.6
4	85.2	84.5	0.8	38.5
5	70.0	70.0	0.0	38.9

PAVEMENT TEXTURE

SURFACE DRAINAGE; CROSS FLOW

Surface runoff must remain the most effective and efficient mode of removing water from pavements. Interceptor in-pavement drains are necessary at intervals to limit a buildup of depth. A porous layer at the surface has limited capacity for piping and discharge and will overflow. However, the instant runoff and overflow cease, emergence of surface asperities begins and drying starts. Time to dry is important because water remaining on a smooth polished surface is lubricative; water remaining cupped in surface macrotexture bears tire loads and is a subtractive influence on tire traction when mobilized.

Crown and superelevation of pavement enhance runoff (10, 11, 12, 13). Grade slopes greater than cross slopes tend to drain water toward sags and to cause water to accumulate toward low points (Figure 6). So-called sheet flow (Figure 2) is sometimes difficult to recognize. Sometimes, superelevated multilane pavements drain large areas toward the inner edge of the curve. Depth increases downgrade. As depth increases, hydroplaning speed decreases. Ponding may be due to faulting at joints. Channeling may arise from rutting in wheel paths.

Large macrotexture (peaks and valleys) relieves pressures under a tire by allowing escape of water. Internal voids and channels serve in a similar way. More waffling would cup water. On the other hand, even open-grid steel floors on bridges have been known to be slick. In some cases, the top edges of the steel have been deslicked with epoxy-sand mixtures.

Grooving of concrete pavements is an attempt to provide drainage channels. Milling and gouging portland cement concrete and (or)

bituminous concrete surfaces induce roughness and macrotexture. Surface treatments such as chip seals and sprinkle treatments provide brief if not enduring texture. Chip-seal treatment is illustrated in Figure 7.

DRUMMING AND HYSTERESIS

Knobbiness causes drumming on the tire and could lead to severe chatter or bounce (skittering) of the wheels during peak traction or in the skidding mode. Drumming consumes energy and increases rolling resistance and causes heating at the tire (hysteresis) due to indentation and imperfect recoil of the rubber. Tire squeal during cornering or severe braking is attributed to recoil of rubber after severe straining and slippage.

RETEXTURING

Whereas pavements could be (and a few have been) sandblasted to correct for critical slipperiness at curves and stoplights, etc., the improvement is temporary under heavy traffic. More lasting improvements have been achieved by grooving (ribbing) surfaces with diamond cutters. Ribbing is usually approximately one-eighth inch in relief. Surface drainage and traction are improved. Wear and polishing diminish effectiveness as time elapses. A rutted or warped surface would not be suitable for grooving. Uneven surfaces may be planed or milled; coarse texturing may prove unsatisfactory.

Retexturing has been accomplished by acid etching, sandblasting, and milling with scabbers, routers, and gougers (Figure 8). Wear by studded tires may serve to maintain a skid-resistant texture. Texturing may be effected by grooving with diamond-studded ganged blades or drums. Fine texturing by present-day milling machines could be economical.



Figure 6. Inadequate Surface Drainage due to Sag and Cross Slope, US 60 West of Lexington; Section Reconstructed.



Figure 7. Portrayal of Idealized Relationship between Size of Aggregate and Depth of Application of Liquid or Emulsified Asphalts. This principle is violated too often. Use aggregate as large as 1 inch (1/2 to 1 inch) as assurance against bleeding. Beware of leaving loose unbonded particles; they can break windshields and windows and make dents.

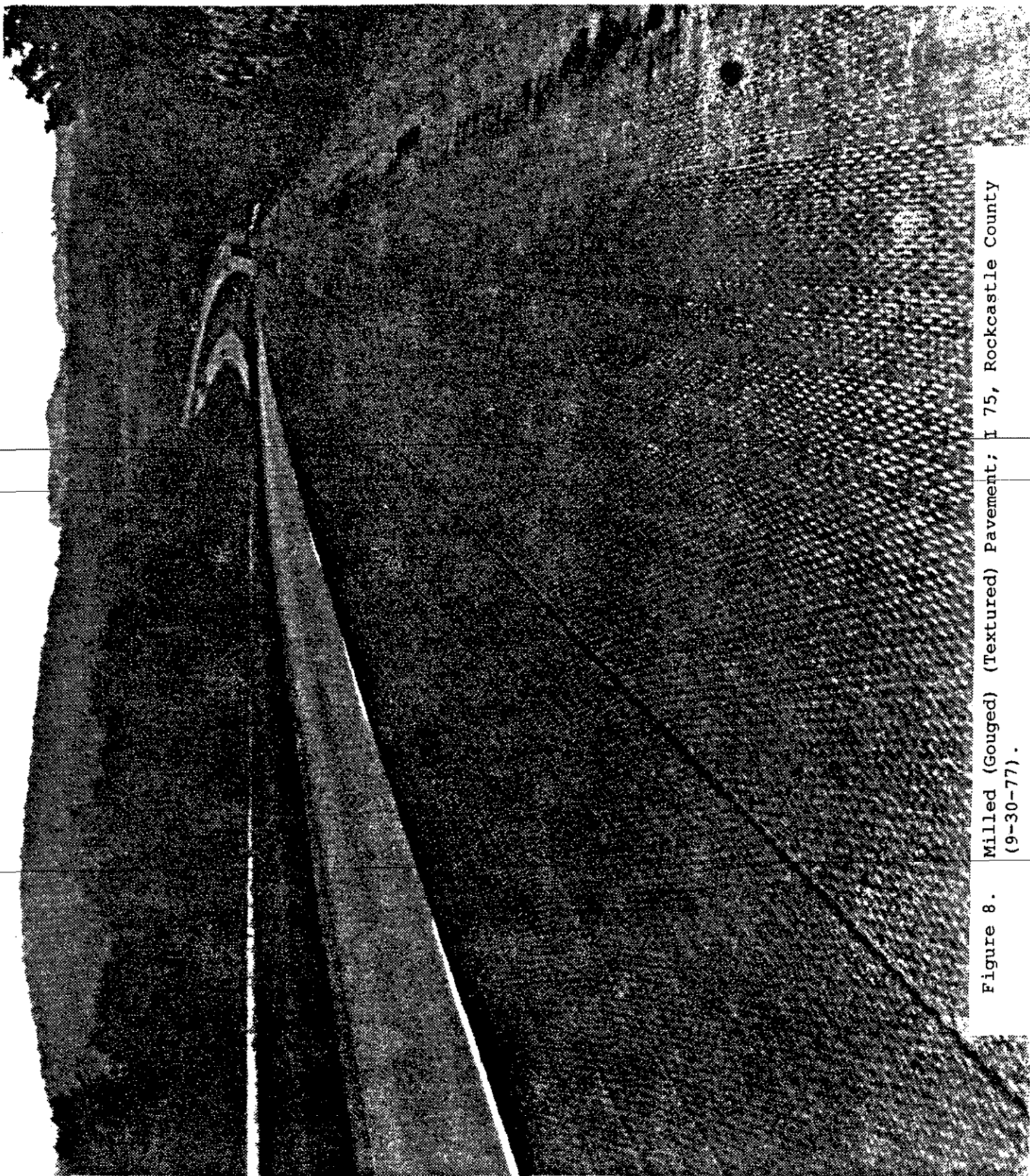


Figure 8. Milled (Gouged) (Textured) Pavement; I 75, Rockcastle County (9-30-77).

Application of sand-slurries -- perhaps broomed -- would be a convenient way of retexturing if curing and durability could be assured. Sprinkle treatments could serve similarly.

SURFACE TREATMENTS

Pavement Rejuvenation: low volatile solvent that penetrates into asphalt and enlivens (softens) it; surface may be recompactd (smoothed); capable of healing some cracks but may create instability.

Sand Seal: light application of liquid or emulsified asphalt (about equal to a good coat of paint) followed by a scattering or full coverage of sand; curing is required; sharp, hard sand is preferred to avoid slipperiness; there is risk of bleeding, loss of sand, and slickness; may suffice for low traffic volumes.

Slurry Seal: emulsified asphalt blended with sand to a soupy consistency; applied with drag-box and screed or doctor blade; proper curing is difficult to achieve. May wash off; may skim over and not cure at depth of application.

Chip Seal: as much as 0.3 gallon of liquid asphalt or emulsion and as much as 30 pounds of aggregate per square yard; nominal size of 0.5 inch; crushed, hard, uniform size aggregate is most favorable; not recommended except for the lightest traffic; aggregate is usually not precoated. Beware of chip seals; they tend to bleed and become slick except under light traffic (see Figure 7). Too much asphalt will tend to drain off the pavement.

Armor Coat: same as a chip seal but employing larger aggregate, such as No. 8's. Any unanchored or loose rock poses hazards to traffic (breaks windshields); most likely uses would be on back roads.

Sprinkle Aggregate: precoated chips scattered onto fresh asphaltic

concrete surface and rolled in; imparts texture and skid resistance; hard, nonpolishing aggregate is required.

ROUNDING AND POLISHING

Figure 9 illustrates very well the flatness, smoothness, and polishing of crushed aggregate particles. Some edge rounding has begun. Rounded and polished grains of natural sand are clearly visible. The areas that are subtractive from tire traction are cumulatively significant. Only the edges of the crushed particles and the fine matrix appear capable of gripping the tire tread and inducing sliding resistance (wet).

Although areas subtractive to traction could be summed and perhaps correlated to skid number, such procedures are not recommended for pavement surface evaluation. Visual observations are sufficient for identification and for relating causes and effects.

Greater reduction in aggregate sizes (to sand) would have broken up larger facets into smaller ones, increased the perimeter (edge) concentration, and probably would have induced a somewhat greater rate of wear and attrition. Rounded natural sand should be avoided.

RENEWAL BY ATTRITION AND WEATHERING

Ideally, perhaps, maintenance or renewal of surface texture should proceed by controlled wearing away of material at a rate that precludes polishing. Whetstones and grinding stones must not dull or clog. Some pavement surfaces suffer too much wear from studded tires. Others merely polish. If aggregate particles weather away too fast, indentations or dimples appear in a surface. This has been observed with some sandstones. Sand-asphalts offer exceptional opportunities for

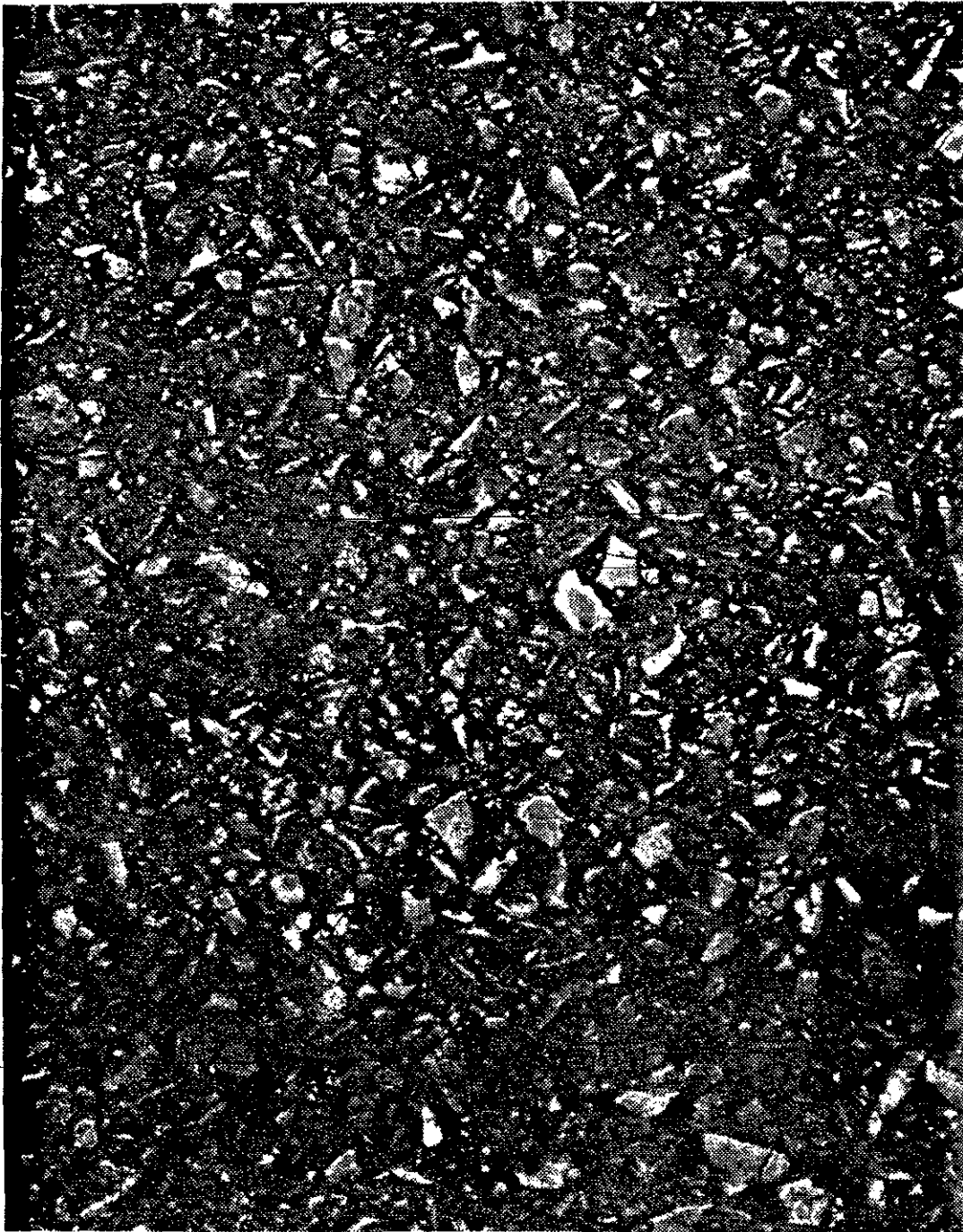


Figure 9. Actual-Size Photograph of Pavement Showing Smooth-Faced Limestone Aggregate. Steel-wheeled rollers and other compactors too, perhaps, tend to orient particles at the surface to present a flat side upward (horizontal). Much wet traction is lost when the edges wear away.

control of surface characteristics favorable to skid resistance throughout (1).

MEASUREMENT OF PERMEABILITY

Open-graded friction courses (OGFC) develop good skid resistance and reduce hydroplaning when properly designed and constructed. Its advantages over Kentucky's dense mixes relative to skid resistance at speed limits are its ability to drain water from the surface and the high degree of macrotexture due to the coarse (open) gradation of the aggregate. It has been observed that many OGFC surfaces in Kentucky appear to densify with the accumulation of traffic, thereby losing the ability to drain water. The densification of the surface would also reduce macrotexture. The imperatives were as follows:

1. Develop and (or) recommend from a search of literature a test procedure for permeability of OGFC surfaces. The procedure should be capable of measuring permeability to a point near densification (void content of 8 percent). Make trial tests on newly constructed OGFC surfaces for a period of time as required, up to one year, to validate and refine test equipment and procedures.

2. Develop and (or) recommend from a search of literature a test procedure for macrotexture of bituminous surface courses. Make trial tests on newly constructed open-graded and dense-graded skid-resistant surfaces as required, up to one year, to validate and refine test equipment and procedures.

3. Equipment and procedures preferably should be suitable for testing the roadway rather than samples taken from the roadway.

Expected benefits were as follows:

1. Determination of the life-cycle effectiveness of OGFC to drain

water from the surface.

2. Development of a relationship between the permeability of OGFC and the skid resistance at 55 mph.

3. Determination of the relationship between the macrotexture of OGFC and dense-graded skid-resistant surfaces and their skid resistance at various speeds.

4. Determination of the life-cycle cost and benefit effectiveness of OGFC and dense-graded skid-resistant surfaces relative to skid resistance at various vehicle speeds (to consider hydroplaning).

The author devised one of the earliest falling-head water permeability devices (Figure 10) for use on Kentucky rock asphalt and sand asphalts in the early 1960's (14). It consisted of a 2-inch diameter pipe section about 2 inches in length. A grease seal was used on the bottom. A cork float and scaled stem in a guide and a stopwatch provided a quick reading. The device proved to be quite adequate.

A larger scale efflux device devised for use on open-graded plant-mixed surfaces was employed by the Federal Highway Administration on Kentucky's first open-graded surface on US 31-W north of Elizabethtown in 1974. Simpler stand-pipe devices (Figure 11) were made by the Materials Division of the Kentucky Department of Highways and used concurrently with the FHWA rigs. It was conservatively viewed then that efflux rates were so great that there was not much need for testing. This was true also in regard to porous bases (15). The Materials Division followed up with several tests on finer porous surfaces.

Open-graded surfaces, especially in eastern Kentucky, were observed later to undergo densification due to in-filling with dirt and mud tracked onto the roads by coal and log trucks and other dirt-road

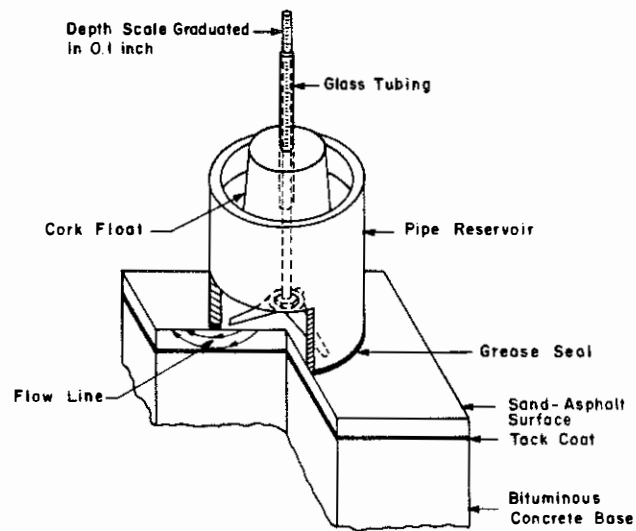


Figure 10. Falling-Head Efflux Pavement Permeability Apparatus (Havens, 1962) (14).

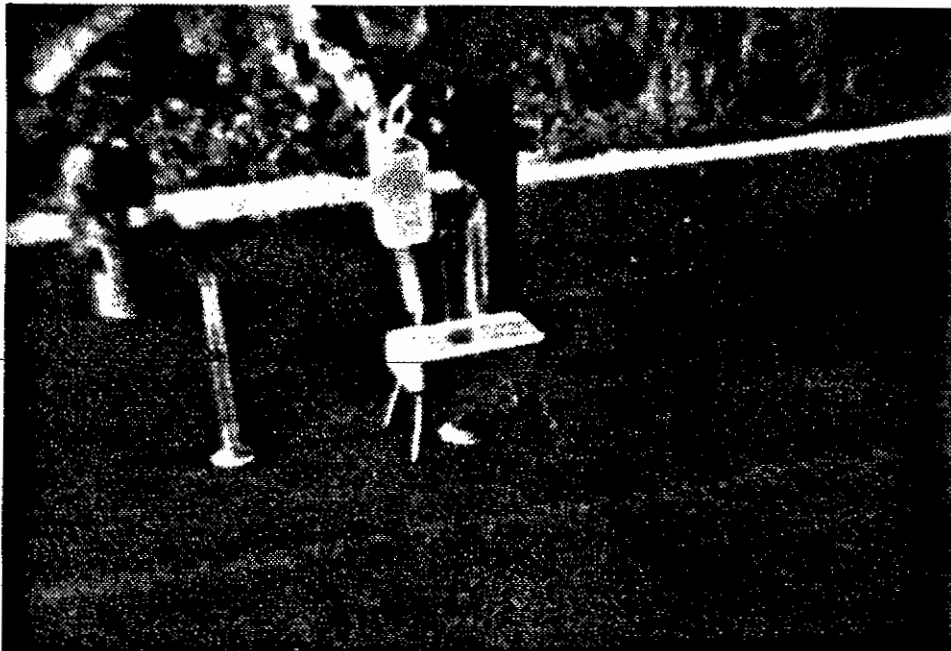


Figure 11. Outflow (Efflux) Devices Contrived by Division of Materials, Kentucky Department of Highways, 1974, for Open-Graded Surfaces and for Coarse and Fine Sand Asphalts.

traffic. The clogging is quite visible.

Horne (6) measured the buildup of pressure of water against tires. He largely confirmed the three-zone portrayal of loss of traction and hydroplaning (Figure 1). It was not surprising that pressure approached the inflation pressure in the tire. The time-to-peak was in the order of 10 milliseconds. Thus, a test for permeability realistically must provide peaking in that time range. Hutchinson, Kao, and Pendley (16) achieved similitude by generating gas pressure (detonating a shotgun shell) in a chamber over a diaphragm over a water blanket in contact with a specimen of pavement. This is illustrated in Figures 12 and 13.

The time to reach tire pressure is related to hydroplaning speed. Hwang (17) measured the pressures under an oblong rigid plate and constructed pressure-space-time plots. Pressures peaked between 5 and 25 milliseconds.

None of the devices shown is very portable or is very convenient to use on the road. For simplicity and convenience, some sophistication must be sacrificed. Figure 14 shows a rubber push-pull pressure-suction cup with a pressure gage. It is capable of generating several pounds of pressure very quickly. It suffices to demonstrate relative air permeability. ~~A percussion feature and pressure transducer was added~~ (Figure 15). It became less portable. An important consideration here and in other devices too is the seal around the perimeter. A stiffer rubber seal may suffice for very smooth surfaces, but a more compliant one is needed for coarser surfaces. Air or gas pressure inside the cup serves to impress the more compliant seal into the valleys and holes. Indeed, a series of layered seals may be optimum. A rigid cup or dome may be employed with CO₂ capsules such as used in BB and pellet guns.

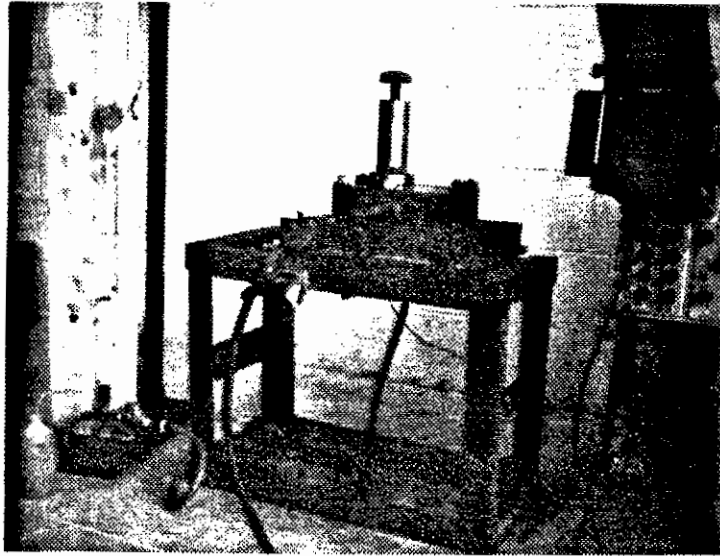


Figure 12. Hutchinson, Kao, and Pendley's Dynamic Permeability Device; Impulse Generated by Discharge of a Shotgun Shell (16).

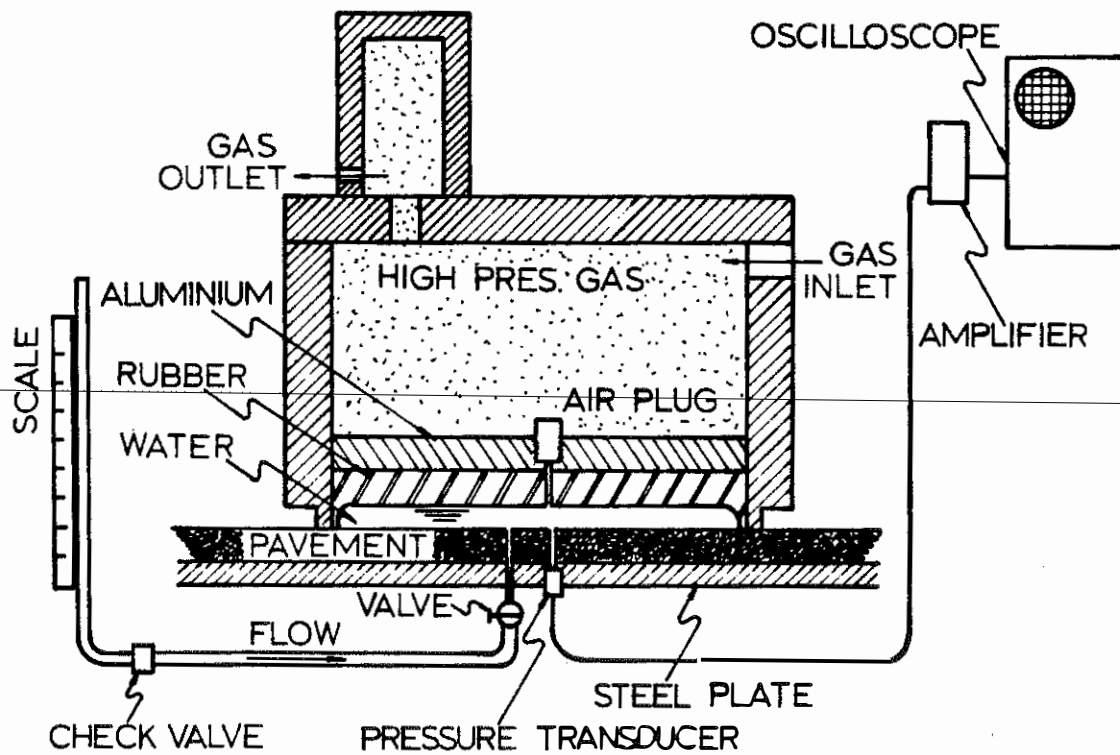


Figure 13. Internal Details of Hutchinson, Kao, and Pendley's Permeability Device (16).

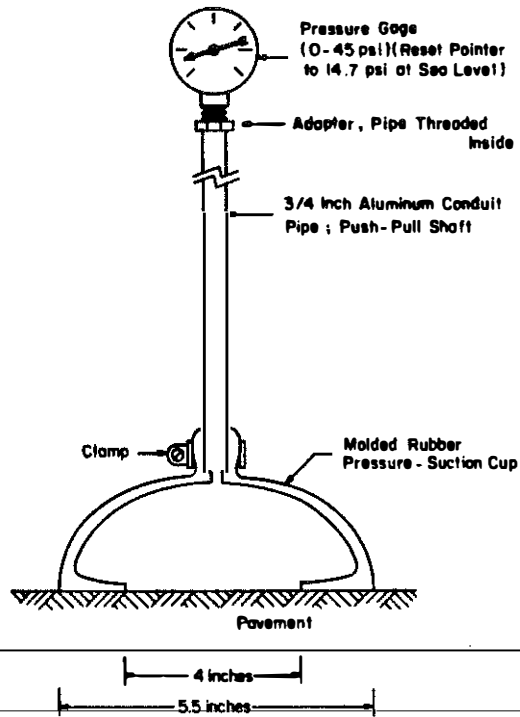


Figure 14. Rudimentary Device for Measuring Air Permeability (Air-Efflux Back Pressure) of Pavement Surface.

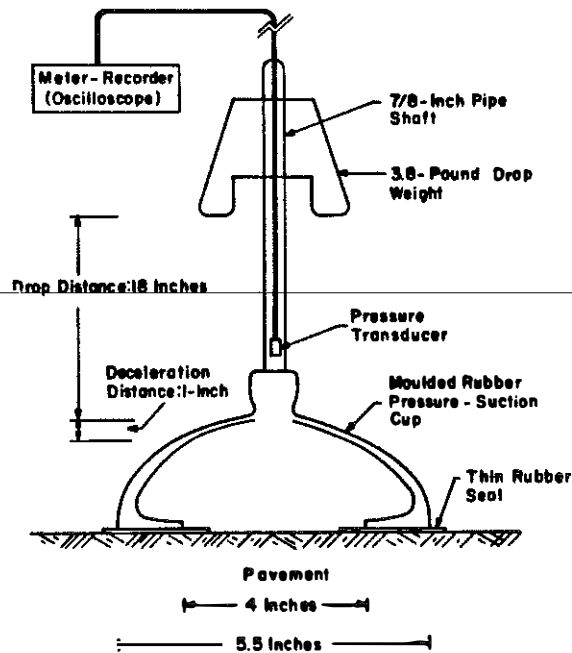


Figure 15. Second-Generation Device for Measuring Air-Efflux Resistance of a Pavement Surface.

Calculations related to the use of a drop hammer to generate a pressure impulse and the degree of similitude that may be achieved are given below:

Impulse generated by falling weight:

Height = 18 inches (1.5 feet)

$V = at$

$S = 1/2 at^2$:

$$1.5 = 32t^2/2$$

$$t^2 = 0.09375$$

$$t = 0.3062 \text{ sec}$$

$$V = 0.3062 \times 32 = 9.8 \text{ ft/sec}$$

Weight arrests in 1 inch of travel (approximately)

$$V = 9.8/2 = 4.9 \text{ ft/sec (average)}$$

$$S = V(\text{average}) \times t$$

$$1 = 4.9 \times 12 \times t$$

$$t = 1/58.8 = 0.017 \text{ sec}$$

Similitude:

$$\text{Time to peak deceleration of weight} = 0.017/2 = 0.0085 \text{ sec}$$

$$\text{Time to impress 4.5-inch long footprint, 54.8 mph} =$$

$$0.375/80.33 = 0.0047 \text{ sec}$$

Area:

$$\pi D^2/4 = 3.14 \times 16/4 = 12.6 \text{ in.}^2$$

Weight:

3.8 lbs.

Subsequently, a piston-type plunger with an O-ring gasket and drop hammer was fitted into a heavy plexiglass hollow cylinder as depicted in Figures 16a and 16b. It was desired to accelerate the hammer through 18

inches of fall and to decelerate through approximately 1 inch of travel after impacting the piston. To generate a pressure of about 30 psig (about equal to auto tire pressure), the travel of the piston must be such that the initial volume of air will be compressed to one-third its volume. This respects the gas law wherein $P_1 V_1 = P_2 V_2$. P_1 is atmospheric pressure (nominally 14.2 psia at 1,000 feet of elevation); P_2 is provided to be 30 psig (44.2 psia). $P_1 V_1 = P_2 V_2$ applies to absolute pressures; thus

$$14.2 \times V_1 = 44.2 \times V_2$$

and

$$V_2/V_1 = 0.321.$$

Volume is proportional to the height of the piston. Therefore, an initial height of 1.5 inches and a final height of 0.5 inch gives a travel of 1 inch and would yield the desired pressure for a no-leakage excursion. If leakage is likely, the piston will impact a cushion at the end of allowable travel. In that event, the pressure will not peak to the maximum. A pressure transducer in the stem indicates the true pressure peak. A unique feature of this contrivance is the absence of external reactance during the pressure rise. After peaking, the weight and cylinder rebound slightly.

The absence of reactance suggested the possibility of using an L-shaped seal inside the base of the cylinder (Figure 16b). A snug fit of the vertical leg or flange would negate need for fixing the seal to the cylinder. Ideally, the horizontal leg would taper toward the inner edge and extend at least an inch or more. If the inner horizontal portion were thin and compliant, no additional seal would be needed. However, L-shaped seals such as this are not standard and would have to be

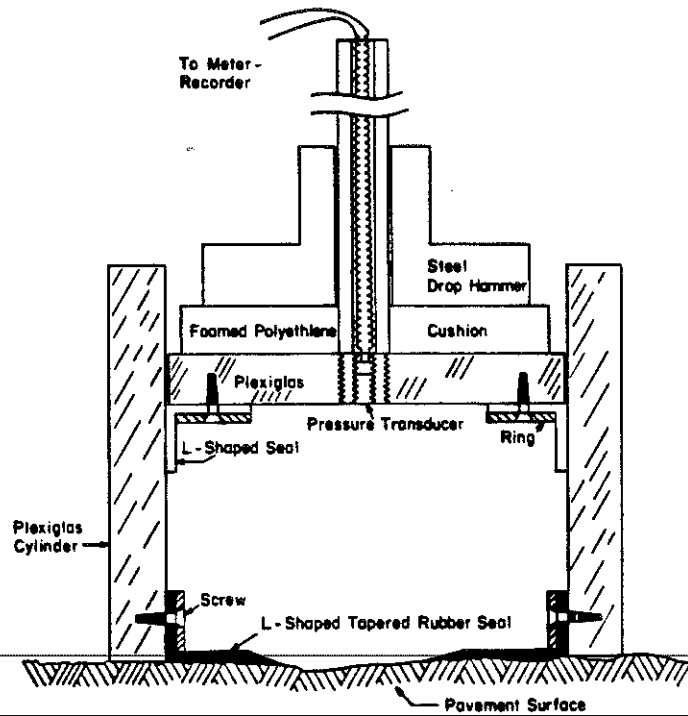


Figure 16a. Conceptual Rendering of Prototype Air-Efflux Resistance-Measuring Device.

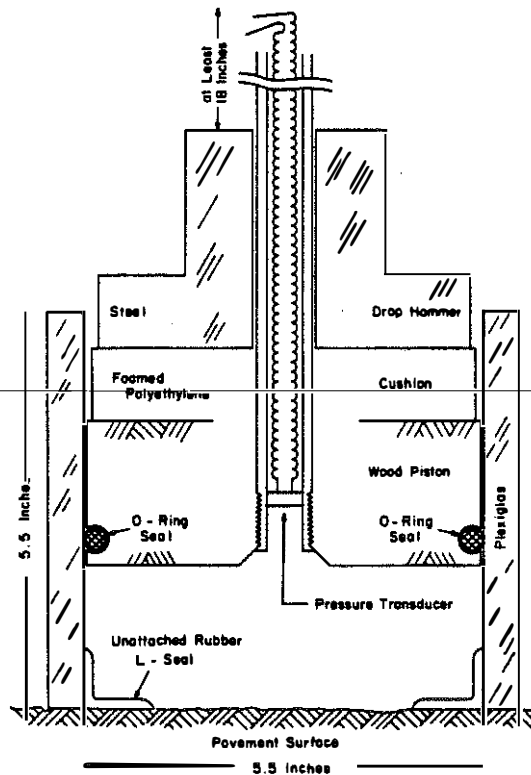


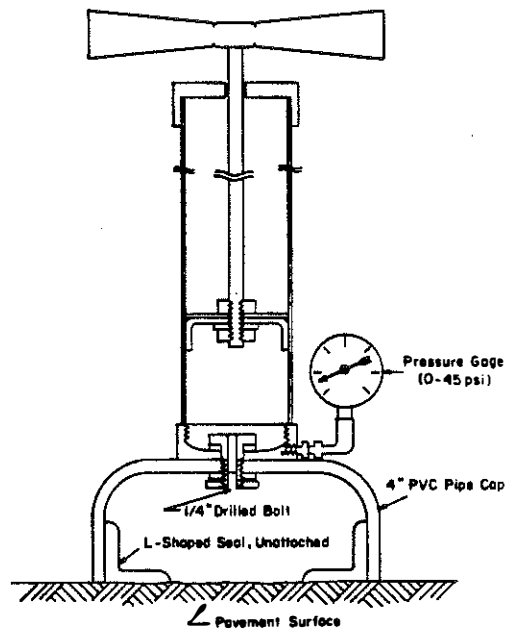
Figure 16b. Prototype Employing O-Ring Piston Gasket and Unattached L-Shaped Seal.

specially molded. This remains a good alternative. A relatively stiffer, but tapered, horizontal flange could be used by laying a thin compliant rubber membrane over it (perhaps with a snug keeper ring or disk to hold it in position). A circular opening at the center, with at least an inch-wide annular or ring of the membrane free to contact the pavement upon application of a slight surge of air pressure.

This device (Figure 16b), with a crudely fashioned L-shaped seal, sufficed for demonstration of principles and for referee purposes.

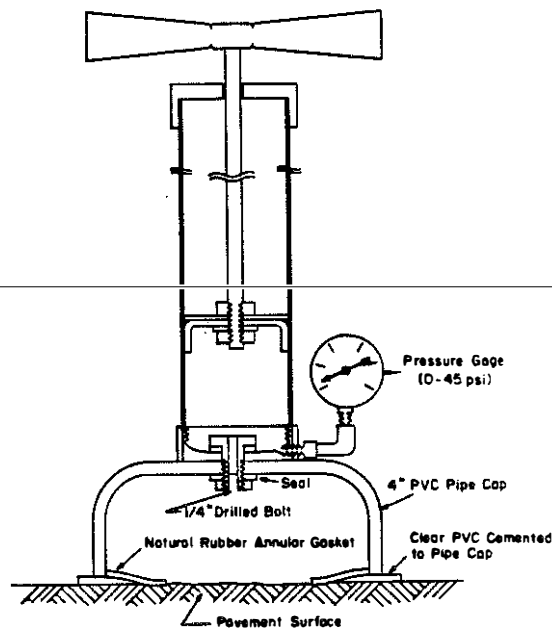
A larger device was fabricated using a 6-inch x 12-inch polyethylene concrete cylinder mold. A circular section of the bottom was cut away leaving a horizontal flange about 1 inch wide. The membrane, with a larger hole, was laid on the flange. The size of the drop hammer needed to induce sufficient pressure was too large.

Finally, the need for an L-shaped seal was circumvented. A smaller device was contrived by modifying an ordinary tire pump. A tire pump was adapted to a dome-shaped inverted cup (a PVC pipe cap, 4-in. inside diameter). L-shaped seals were improvised -- with some success (Figure 17). Because of threshold seal-seating pressures prerequisite to the test, it became necessary to reduce the test area. The reactance to 30 psi air pressure on 12.57 sq in. would be 377 lbs. This had to be decreased to not more than the body weight of a man. A flat sheet of clear PVC, nominally 1/8 inch thick, was glued to the bottom rim (Figure 18). A hole, nominally 2.5 inches in diameter, was cut at the center of the sheet, and the inside surface was tapered sharply. The principal element is the seal. It was cut from a flat sheet of natural rubber, which was nominally 0.020 inch thick. The outside diameter is 3.4 inches; the inside diameter is 2.0 inches (open area is π sq in.). The



Footrests not Shown

Figure 17. Simplified Device for Measuring Air-Efflux Resistance of Pavement Surface. Tire pump is used to generate pressure impulse to seat seal (unattached) against wall of air chamber and against pavement. Air chamber must be held against pavement by operator's feet. Pressure thrust by operator may cause liftoff and loud blowout if pavement is smooth and seal is effected.



Footrests not Shown

Figure 18. Revised Model of Simplified Field Device that Does not Require L-Shaped Seal.

seal lays inside (over) the tapered flange of clear PVC. It is weighted by several annular, flat, rubber gaskets. The volume of the air chamber may be varied by inserting or removing those dummy gaskets. The active seal is approximately 1/2 inch wide (annular). Seating against the pavement is accomplished by thrusting the pump shaft downward and inducing a surge of air in the cup. A pressure gage was installed in the air-base connection.

A seal is effected easily on a smooth non-porous surface. Seating of the seal may be observed by looking at it through the bottom of a glass plate supported on a ring stand (a mirror facilitates the observation).

The efflux-resistance of the air (highest gage pressure achievable during a quick-thrusting stroke of the pump) is the parameter read. Pressure-volume relationships ($P_1V_1 = P_2V_2$) otherwise limit the maximum pressure. Approximately 30 psig is achieved on a very smooth surface. Foot brackets are provided for hold-down reactance. Ranges of pressure readings may be demonstrated on standard or reference surfaces such as glass, linoleum, paper, cloth, sandpapers, and grooved and ribbed plastic sheets.

~~This device (Figure 19) was chosen for field surveys.~~

A preliminary survey of pavement surfaces was performed in the fall of 1984. A more extensive survey followed in late summer and fall of 1985. These were not inventory-type surveys nor random samplings; they were tests on a cross section of surfaces of the several types, a selective sampling. The results are given in Table 2.

Air-efflux resistance correlates best with that which can be seen by the unaided eye; that is, if the surface appears smooth and non-porous,

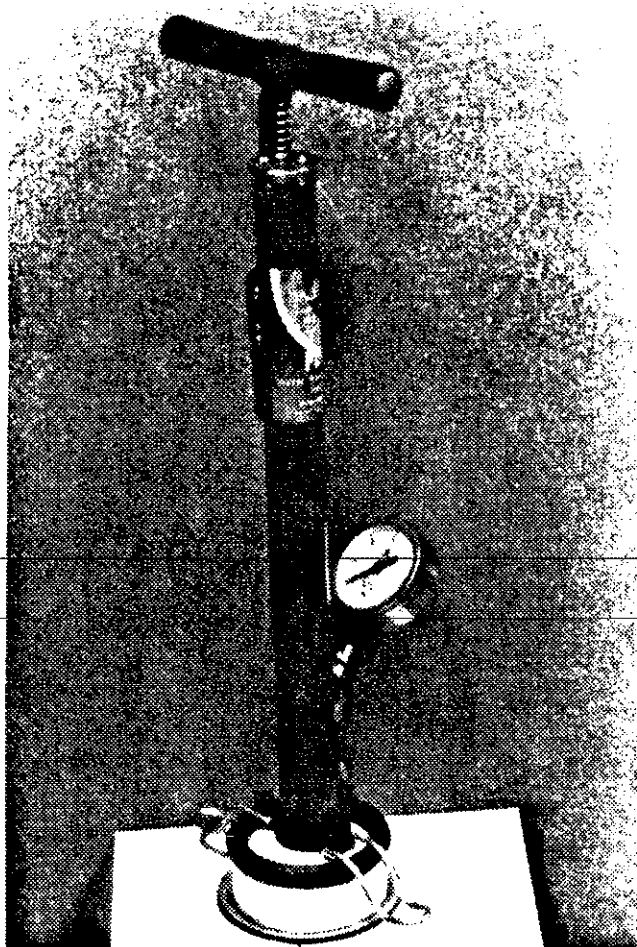


Figure 19. Photograph of On-Road Air-Efflux Tester. Note footrests and rubber ring cushion.

TABLE 2. RESULTS OF FIELD TESTING OF AIR-EFFLUX TESTER

ROUTE	CITY OR COUNTY	DIRECTION OF TRAVEL	MILEPOST	SURFACE TYPE	AIR-EFFLUX TESTER READINGS (psf)								DATE OF TESTING
					EDGE	1ST WHEEL PATH	BETWEEN WHEEL PATHS	2ND WHEEL PATH	CENTERLINE	3RD WHEEL PATH	BETWEEN WHEEL PATHS	4TH WHEEL PATH	
KY 4	Fayette	CC	3.0	OGFC		10							12-14-84
			4.3			8							
			7.0			18							
		C	8.0			12							
			8.0			5							
			7.0			4							
US 25	Fayette	SB	4.3	Dense		2							12-14-84
			7.3			12							
			6.3			11	} 40% Nat S						
			4.8			12							
			3.5			14							
			2.8			12	} NB Lane — 12 where not dusty from La quarry operation						
			2.0			16							
			1.1			12							
			0.1			16							
I 75	Madison Fayette	NB	On Ramp	OGFC		0							12-14-84
			100.0			0							
Bolivar St.	Lexington	WB		SA		20							12-14-84
US 60	Woodford	EB	11.0	POC	11	20		21					12-17-84
		WB	Verailles Bypass	AC		18		18		19		18	
Tates Cr Rk	Lexington	SB	At Turkeyfoot	AC		27		27		27			09-09-85
						25		22		25			
KY 4	Fayette	CC	17.0	AC		20		20		20		20	09-09-85
			16.0			25		22		20		19	
US 25	Fayette	SB	9.3	AC		25		25		20		25	09-09-85
			7.3			20		19		20		19	
			6.3			19		19		19		19	
			2.0			20		20		20		19	
I 75	Fayette	SB	98.0	OGFC	2	12	12	12				0	09-09-85
		NB	100.0			19	8	11				5	
		NB	On Ramp			6		10					
KY 627	Clark	EB	0.2	SA		20		20					12-17-84
		WB	0.2			20		20					
		EB	1.0			20		20					
		WB	1.0			20		20					
		EB	2.0			20		20					
		WB	2.0			20		20					
		EB	3.0			20		20					
		WB	3.0			20		20					
		EB	6.0			22		20					
I 64	Clark	WB	6.0	AC		24		22					12-17-84
		EB	95.4			12		15		16		18	
	Paris Bypass	NB	2.1			10		14		5		2	
		SB	2.1			12		6		15		10	
		NB	1.6			12		10		18		12	
		SB	1.0			7		7		16		17	
		NB	Pat Spot							24		22	
		SB	0.5			7		14		5		12	
		NB	7.0			10		8		16		22	
		SB	7.0			14		12		14		20	
US 460	Bourbon	NB	8.0	AC		11,16		19		20		11	12-17-84
		SB	8.0			19,17							
								25(Fat Spot)					
US 460	Bourbon		0.1 mi from US 68-27	AC		5		10		10		11	12-17-84
US 68-27	Bourbon		0.5	AC		20		19		20		21	12-17-84
KY 353	Fayette	SB	7.8	AC		19		20		18		15	09-07-85
		SB	5.0			20		20		19		19	
		Bourbon	*			20		20		20		21	09-09-85
		Fayette	*			22		20		20		21	
		SB	7.8			19		20		18		15	12-17-84
		SB	5.0			20		20		19		19	
US 60	Fayette	WB	3.6	POC		17		19					12-17-84
			3.0			17		16	} Grooved but worn				
			0.0		3	21		21					
US 119	Barlan	SB	11.8	AC		20		20		22		20	09-12-85
			5.1	OGFC		20		20		19		14	
US 25E	Bell	WB	14.7	OGFC		19		20		20		20	09-12-85
			18.1			17		5		15		10	
	Knox	WB	19.0			12		12		Patched		Patched	
			3.0			12		12		10		10	
I 75	Gardner	NB	Mt Vernon	OGFC		0		2		5		6	09-12-85
		SB				20		20		6		4	
	Madison	NB	95.0			16		15		9		5	
		SB	95.0			3		3		3		3	
US 23	Greenup	NB		Seal	0	20		20					11-14-85
						20		21					

* Each side of county line

Abbreviations (used in Tables 2 and 3)

Phos	Phosphate
WBB	Wet-Bottom Boiler
SA	Sand Asphalt
Cl I	Class I
PCC	Portland Cement Concrete
Cl I, A & A Mod	Classes I, A, and A-Modified
OGFC	Open-Graded Friction Course
ST	Sprinkle Treatment
GRG	Green River Gravel
Nat S	Natural Sand
Ls S	Limestone Sand
GR Sand	Green River Sand
Ls	Limestone
Styrelf	Proprietary Rubberized Asphalt, in Chip Seals
Cr Chert	Crushed Chert
Gr	Gravel
CE	Corps of Engineers
59B	Special Provision (Sand Asphalt)
C	Clockwise
CC	Counterclockwise
EB	Eastbound
WB	Westbound
NB	Northbound
SB	Southbound
AC	Asphaltic Concrete

the efflux resistance pressure will be high. It measures the tendency to hydroplane. A significant back pressure of air, together with stroke speed of the pump, translates into a more severe effect on the skid resistance of a tire when water and real time are brought into play. A similitude factor may be inferred -- but perhaps needlessly.

It is to be remembered that skid tests with a trailer have been made at speeds of 60 and 70 mph, far above hydroplaning speeds. When testing, 1/8 inch of water is laid down; and that depth is not sufficient to cause total hydroplaning of even a ribbed tire. However, the skid number generally decreases as speed increases. Of course, some heating and steaming of water occurs at the upper speeds. Any laydown of tread rubber suggests melting of rubber and further lubrication. Therefore, skid trailers yield wet friction values but yield no information about hydroplaning pressures or speeds. Those must be measured independently (with greater depths of water). The air-efflux resistance tester is now the only device that uniquely relates to hydroplaning potential. Skid trailers may be used over impoundments of water on pavements. The depth of water would there be a controlled variable.

A more specific interpretation and example follows under Interpretation and Correlations with Skid Data.

SCANNING ELECTRON MICROSCOPY

The purpose of scanning electron microscopy (SEM's) was to prove the physical principles that lead to slipperiness; that is, rounding and polishing of aggregate particles and (or) the absence or loss of

asperities and (or) loss of sharp, gouging, gripper points. Those aggregates susceptible to rounding and polishing will be identified. Hammer-and-chisel chips obtained from pavements (outer wheel-paths) tested by ASTM E 274, Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire, were observed and elementally analyzed by SEM methods, photographed, and arrayed according to SN_{40} values. Some aggregates previously classed as skid resistant have not performed as well as expected. SEM work completed confirmed rounding and polishing. Surfaces having high skid resistance have not exhibited those characteristics under SEM examination. Magnifications of 30x and 300x have been found suitable.

Although some SEM equipment has the capability of portraying macro- and micro-profiles, the main effort thus far has been toward detection of polishing and the presence of glassy and smooth surfaces. Identification of offending aggregates would, in itself, be a worthy achievement. SEM equipment usually displays a particle in the surface of a chip, and accessory equipment displays the elemental composition of any pin-pointed area in the view.

How typical is the chip? How well does it represent a pavement? Indeed, several chips may be taken, but detection and identification does not necessarily invoke statistical sampling routines. Independent associations of profiles with skid-resistance values would require extensive sampling.

It is theorized, of course, that each area of polishing and rounding or of micro-range smoothness subtracts from the otherwise tractive gross area. ASTM E 770-80, Standard Test Method for Classifying Pavement Surface Textures, originally advanced by Schonfeld (18), utilized

stereo-pair photointerpretation to resolve six textural parameters describing peaks and valleys, rounding, etc. Previously, the parent schema (ASTM E 559-75T, Tentative Recommended Practice for Classifying Pavement Surface Textures Suitable for Skid Resistance: Photo Interpretation) included direct associations with skid numbers (a method of estimating skid resistance). Because of inaccuracies, that part was not included in E 770-80. Eventually, the association may be refined and restored.

Several investigators have advanced the idea that the British portable tester (pendulum) is largely sensitive to microtexture. This is because of the very slow speed of the wiper (less than 5 mph). The drag on the pendulum is, therefore, due considerably to hysteresis heating and hardness of the rubber wiper. Viscous drag and hydrodynamic pressures are low. Macrotexture has been presumed to be a gross parameter that may be quantified by sand-patch or grease-patch tests. Horne and Buhlman (19) found no relationship between those factors and skid resistance. They did find a relationship between those factors and speed gradient. Others have claimed varying degrees of success in quantifying attributes of surfaces related to traction (19, 20, 21, 22). Inability to achieve a high degree of correlation merely indicates the complexity of the contributing factors. This does not diminish the validity of skid tests (23). Areas found by microscopic inspection to be rounded, polished, glassy, and otherwise smooth are considered subtractives from the gross tractive area of the tire print.

IDENTIFICATION OF SPECIMENS AND ROAD DATA

Forty-two chips were examined. Locations and project data are given in Table 3. Specimen 0 was preliminary. Favorite projects were

TABLE 3. LOCATION AND ATTRIBUTES OF SEM SPECIMENS (CHIPS) FROM WHEEL PATHS OF PAVEMENTS

SPECIMEN	ROUTE	MP	LANE	COUNTY	TYPE OF SURFACE	AGGREGATE	DATE OF PAVING	TRAFFIC VOLUME*	AVERAGE SN*	
1	I 264	16.2	EB	Jefferson			5-78	84,630(81)	42.5(79)	45 (82)
2	I 264	16.2	WB	Jefferson	CI AA	Phos Slag WEB Slag	5-78	84,630(81)	49 (79)	44 (82)
3	I 264	12.6	WB	Jefferson	CI AA	Phos Slag WEB Slag	10-79	96,150(81)	49 (79)	27.5 (82)
4	I 264	9.8	WB	Jefferson	CI AA	Phos Slag WEB Slag	10-79	65,200(81)	49 (79)	27.5 (82)
5	I 264	9.8	EB	Jefferson	CI AA	Phos Slag WEB Slag	10-79	65,200(81)	43.5(79)	25 (82)
6	I 264	12.6	EB	Jefferson	CI AA	Phos Slag WEB Slag	10-79	96,150(81)	43.5(79)	
7	US 62	6.7	EB	Harrison	SA Type II	100% Slag	10-75	2,990(77)	56.5(79)	51 (81)
8	US 27	10.3	NB	Harrison	CI Type A		66	2,310(81)	46 (75)	
9	Euclid Ave		WB	Fayette	SA Type I	75% Nat S 25% Ls S	8-74	15,450(79)		
10	KY 1974	Tates Creek 500' South of Cooper	SB	Fayette	SA Type II	75% Slag 25% Nat S	8-77	19,293(81)	37 (79)	
11	KY 1683	Reynolds Road	EB	Fayette	SA Type II	75% Slag 25% Nat S	8-77	7,160(75)	43.5(79)	
12	US 27	2	NB	Campbell	SA Type I		8-63	3,537(81)	45.5(79)	
13	I 64	67.5	SB	Woodford	FCC		9-73	14,001(81)	32.5(79)	
14	US 25	14	SB	Madison	OGFC Type I Slag		76	11,734(81)	50 (81)	
15	US 25	17	SB	Rockcastle	CI I A&A Mod		74	3,734(80)	43 (75)	
16	I 75	63	NB	Rockcastle	CI I A&A Mod		9-77	21,376(81)	41.5(79)	45 (82)
17	US 27	16	NB	Lincoln	SA Type II	100% Slag	9-76	6,626(81)	45 (81)	
18	US 68	1	EB	Bourbon By Pass	OGFC		11-76	8,217(78)	56 (79)	60 (81)
19	KY 57	4.1	NB	Fayette	SA Type II	75% Slag 25% Nat S	6-77	951(81)	58 (79)	
20	US 60	7.3	WB	Franklin	SA Type II	100% GR Sand	11-78	19,347(81)	32.5(79)	
21	US 60	11.3	EB	Franklin		75% Nat S 25% LsS	7-74 7-75	27,088(81) 2,660(81)	43 (79) 49 (79)	
22	Mt P'way	57.5	EB	Wolfe- Magoffin	SA Type I CI I A Mod					
23	US 62	21	WB	Hardin	OGFC Type I	90% GRG 50% Ls	10-76	3,008(81)	49.5(79)	51 (82)
24	US 31W	1.5	NB	Meade	SA 59B	100% GRG	10-72	11,475(79)	45 (79)	
25	KY 55	9	SB	Taylor	OGFC Type I	60% GRG 40% Ls	9-78	4,761(81)	36 (9-78)	
26	US 31E	20.1	SB	Nelson	ST Control	Ls	9-78	4,149(81)	51 (79)	54.5 (82)
27	US 31E	16	SB	Nelson	ST Quartzite	Quartzite	9-78	4,910(81)	47 (79)	53 (82)
28	US 31E	17	SB	Nelson	ST Slag	Slag	9-78	4,910(81)	54 (79)	56.5 (82)
29	US 31E	18	SB	Nelson	ST GRG	GRG	9-78	4,149(81)	55.5(79)	58 (82)
30	US 31E	19	SB	Nelson	ST Granite	Granite	9-78	4,149(81)	57 (79)	58 (82)
31	31H ByP	2	NB	Gardin	FCC		11-74	6,640(81)	37 (79)	61 (81)
32	I 75	155	NB	Grant	Chip Seal	Styrelf	8-81	25,229(81)	51 (79)	38.5 (82)
33	KY 7	0.7 mi to Henryville	EB	Perry		Sandstone	80	3,209(81)	50 (81)	56 (82)
34	KY 15	2 mi to End of Proj	NB	Knott		Sandstone	71 CE Overlaid	3,865(81)	55.5(81)	
35	I 24	17	EB	McCracken	OGFC Chert	Cr Chert	9-77	12,745(81)	60 (79)	56 (81)
36	I 24	25	WB	Marshall	OGFC Slag	Slag	10-77	11,875(81)	43.5(79)	35.5 (81)
37	US 62	6.7	WB	Muhlenberg	OGFC Slag		10-76	3,569(80)	53.5(79)	50 (81)
38	I 24	30	EB	Livingston	CI I AA		79	10,161(81)	43 (81)	44 (82)
39	KY 55	7	SB	Spencer	CI I AA		79	3,493(81)	51.5(79)	55 (82)
40	US 60	5	EB	Ballard	OGFC Type II	100% Gravel	75	6,111(81)	38.5(79)	44 (80)
41**	KY 94	23.5	EB	Calloway	OGFC Type II	70% Gravel 30% Ls	78	2,598(79)	50.0(79)	
42	I 64	101.7- 112.4		Montgomery	CI I		73	9,270(81)	48 (79) 44 (81)	51 (82)

* Year in ()

**Overlaid 7-81

sampled, and matching concurrent skid-test data were not available in several cases. The sampling largely represents skid-resistant surfaces. Only the 1979 surfacings of the Watterson Expressway and US 60, Franklin Co, MP 7.3, qualify as being slippery.

PHOTO PRESENTATION

SEM photos are presented in the APPENDIX. Explanatory notes are given at the beginning.

Specimen 0, not enumerated in Table 3 was taken from KY 1964, MP 2, Woodford County an all-limestone surface. Traffic was low, and early skid tests indicated high skid resistance (SN 60). The project was chosen from a listing of skid test survey data. However, the chip specimen was taken (September 1982) about two years later. Rounding and polishing had advanced enough to illustrate the process. Unfortunately, contemporary skid tests were not made.

INTERPRETATIONS AND CORRELATIONS WITH SKID DATA

Tendencies toward polishing and smoothness were detected in some specimens not showing high skid resistance. High skid resistance is not associated with this tendency. Smoothly cleaved or fractured surfaces (flat and horizontal) appear to contribute to slipperiness. This is true even of hard mineral particles such as quartz. Mixed generic aggregates may be sorted and compared microscopically.

Quantification of attributes for the purpose of predicting (estimating) skid-resistance values is beyond the present scope of work. It suffices presently to recognize and identify trends and tendencies toward polishing, smoothness, and absence of grippers as the slippery elements.

The purpose here has not been to engage in the tedium of measuring flatness and polishing with great accuracy as in the case of the Schonfeld method (18). The purpose has been, however, to show in convincing ways that the physics and mechanics of tire traction are understandable. Understanding will guide future decisions and eventually will lead to safer pavement surfaces.

SEM together with air-efflux resistance measurements reveals the significant attributes of the pavement surface.

Consider for example that a pavement surface is composed of 40 percent coarse aggregate that is flattened and polished. It is readily lubricated by water. In reality, there may be some fine aggregate that is flattened or rounded and polished, too. Add 5 percent to the 40 percent already mentioned. By recourse to Equation 8, let the dry friction coefficient equal 1. This will be diminished by $(1 - A_s/A_t)$. Thus:

$$f_w = f(1 - A_s/A_t) = 0.55$$

This compares to an average high of SN_{40} of 0.55.

A further reduction occurs due to surface density and smoothness. That is the hydrostatic back-pressure of the surplus water under the tire. This increases in proportion to V^2 . From Horne's empirical equation (6, 7) mentioned before, $V^2 = 107 P_i$. Here, however, let $V^2 = 107P_h$ and $V = 40$ mph; then, $P_h = 15$. So, for a polished pavement subject to hydroplaning,

$$\begin{aligned} f_w &= f(1 - A_s/A_t)(1 - P_h/P_i) \\ &= 1(1 - 0.45/1.00)(1 - 15/32) = 0.26. \end{aligned}$$

Lastly: $SN_{40} = 0.26$

The foregoing example should not be construed as a supplantation of road tests by skid-test trailer methods. The trailer remains the referee method of evaluating performances of materials and innovations on the road.

The SEM's and examinations with optical microscopy, together with the equations hypothesized here, suffice to explain the less than superb performance of sand-asphalt surfacing on Muldrough Hill near Fort Knox (Special Provision 59-B). That sand asphalt contained crushed quartz sand (Caseyville, Green River Sand Co.). The larger quartz particles cleaved smoothly, and those flat surfaces were oriented predominantly in a horizontal plane by the compaction roller. The skid resistance remained higher than average but did not excel all others. Open-graded friction courses proved to be superior. Admiration for sand-asphalts waned. Unfortunately, there simply was too much flat smooth area; and the concentration of grippers and sharp edges was not high enough. That was a dense, highly stable mixture. The quartz gravel should have been crushed to a smaller maximum size.

CONCLUSIONS

The use of a falling weight and its deceleration by a cushion of air to achieve time-pressure similitude of a tire appears valid. Objectives (see imperatives under Measurement of Permeability) drawn previously are, therefore, modified and adapted to the reality now recognized. Indeed, success is more assured by measuring the real affecting factors than by measuring less directly related permeabilities.

Polishing of aggregate particles is detectable by SEM examination of chips from the wheel paths of pavements. It is possible to view texture at magnifications not achievable by light microscopy. The limitation there is objective-to-object distance and depth of focus.

The reduction in skid resistance due to the efflux resistance of water under the tire may be expressed as $(1 - P_h/P_i)$; and P_h may be approximated by $v^2 = 107 P_h$.

Hard aggregates crushed to 3/8-inch nominal size may display nearly flat or smooth cleaved surfaces. Only the edges are sharp. Those surfaces (areas) influence traction in a subtractive way. On the other hand, further crushing (to sand sizes) would increase the concentration of sharp edges per unit of area. In this way, maximum benefit may be derived from otherwise hard durable aggregates -- such as quartz gravels, cherts, so-called wet-bottom boiler slags, some steel slags, and phosphate slags. Sandstones may suffice in larger sizes because any fracture or cleavage exposes a sandpaper texture. Some sandstones, however, are composed of rounded sand. Vesicular aggregate such as scoria may suffice in any size. Conchoidal and glassy fracture surfaces may appear in manufactured sands, but sharpness of edges and corners is essential. It is necessary to make sand unless the parent material is vesicular or is like sandstone.

It is postulated that hard sharp sands in a porous, well drained sand-asphalt type surface will excel all others in skid resistance. Dense sand asphalt will give good traction below hydroplaning speeds.

Coarse-grained limestones are known. Some may wear away and erode without polishing. A case in point is a Richmond Limestone (Montgomery County Stone Company, north of Mt. Sterling), together with Walker's

(Menifee County) sand, that performed very well on I 64 (MP 93.5 - MP 110) in a surface for over 10 years. The 1979 skid numbers were 44 and 48. Surely, that aggregate and others similar thereto will be studied more intensely in the near future.

Sacrificial wear and grain attrition remain the ideal process of grit renewal and restitution of sharpness in the surface. If the desired wear is not achieved from normal traffic, artificial or forced wear may become necessary. Carbide studs in some tires may be advantageously permitted on some pavements.

Those elements in a pavement surface that influence skid resistance in a subtractive way may be roughened or abraded to restore sharpe edges and grippers. Retexturing awaits refinement of milling machines to do the specific job.

Determinations of life-cycle costs and benefit effectiveness are beyond the reach of this study.

RECOMMENDATIONS

It is recommended that aggregate for open-graded friction courses be ~~reduced in size: nominally to 1/8 inch. This would increase the~~ concentration of grippers and cutters and would maintain internal drainage for relief of surplus water under tires.

It is recommended that on-road experiments be undertaken to merge the best attributes of sand-asphalts with those of open-graded friction courses to achieve an open-graded, durable, high-friction, renewable surface. This would be a continuation of directions propounded in a preceding report (1). The planner should select hard natural sands and

(or) crush hard parent material such as the Caseyville and Rockcastle conglomerates. The Kentucky River sand (Frankfort) was sharp, though small. The US-60 hill by the armory and in front of Kentucky State College was surfaced with sand-asphalt containing the Kentucky River sand (dredged upstream). It lasted far beyond the expected 7 years and until the roadway was reconstructed. There was never a complaint of slipperiness during its time in service. Farther east, the Kentucky River sand was blended with other sands, but the performance there never quite equaled that on the hill section.

It is recommended that sand-asphalts be laid nominally 1/4 to 3/8 inch in thickness and that methods of patching or otherwise repairing blemishes be developed to compliment the use of that type of surface.

It is recommended that pavement surface drainage be improved wherever possible. Cross surface drainage should be prevented by interceptors in the pavement.

It is recommended that recourse be made to advisory speed signs. The message might read: REDUCE SPEED 10 MPH BELOW SPEED LIMIT WHEN RAINING.

IMPLEMENTATION

The principal benefits to be derived from these studies are in terms of greater understanding and insights into the causes of slipperiness and in guiding the directions recommended. The examination of pavement chips by SEM and the air-efflux resistance tester should be useful in the road testing of aggregates and paving mixtures being evaluated under Study KYHPR-84-98, Native Aggregates for Skid Resistance. Aggregates

and mixtures previously studied and proposed for consideration (1) should be included in any planned performance testing (experimental projects).

Recourse to experimental surfacings should be resumed inasmuch as the so-called open-graded friction course has recognized defects and disadvantages. It would be improved by reduction of aggregate size and by thinner applications. Experimentation with sand-asphalts (both dense and open-graded) should be renewed as recommended herein.

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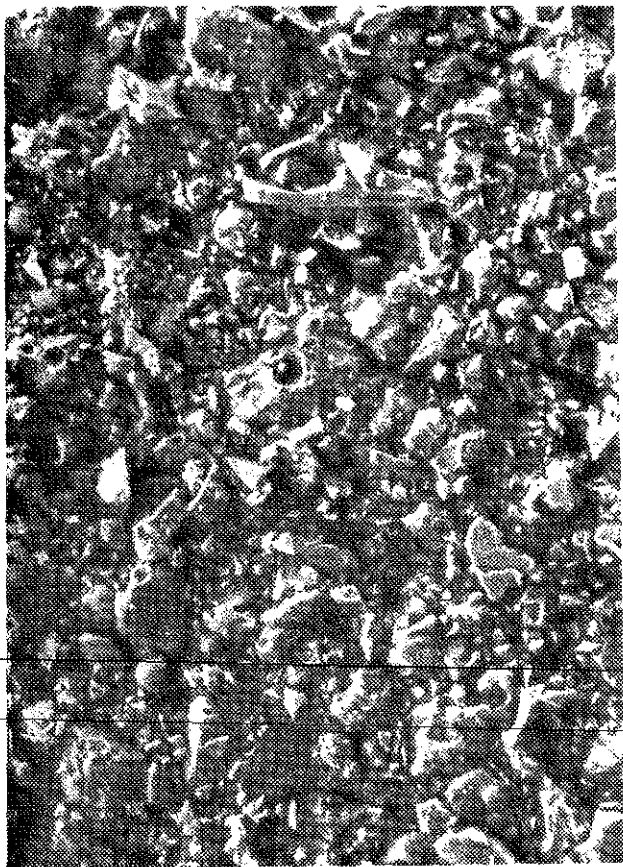
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APPENDIX

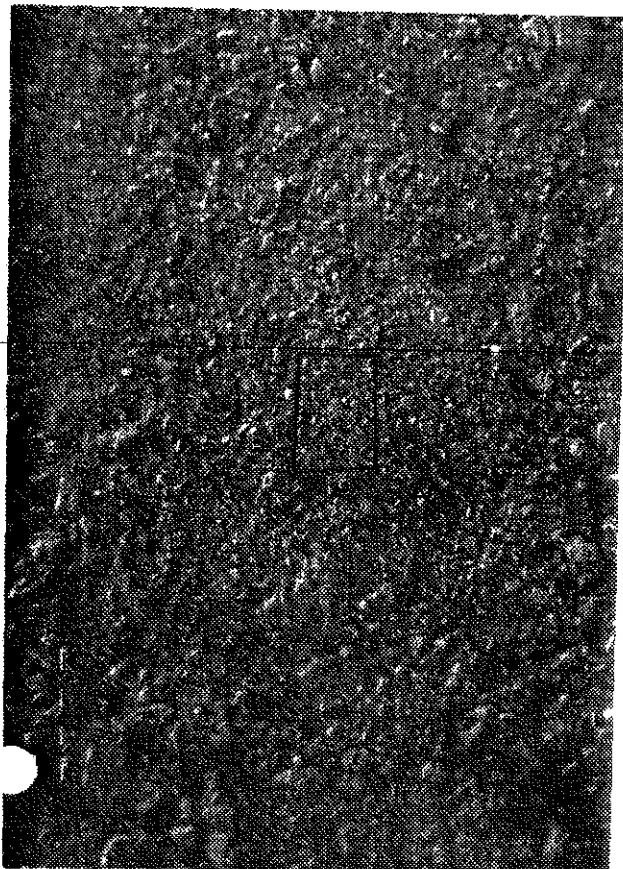
SEM's OF PAVEMENT CHIPS

Explanation of Scale: White dash marks in upper left corner of photographs are indicators of scale and magnification. The last dash rightward is 0.1 micron; each dash preceding is a 10X multiplier. Thus, if the 0.1-micron dash is 0.3 cms in length, and is preceded by three short dashes, the magnification is 30x (1 micron = 1×10^{-4} cm).

Explanation of Enclosures Drawn on Photos: Where matched, the enclosure drawn on the photo at left defines approximately the window that was enlarged in the photo to the right. Elsewhere, the photo at right is of a scene outside the area of the photo at left.



Specimen 2, I 264, MP 16.2, WB, Left: 30X; Right: 300X

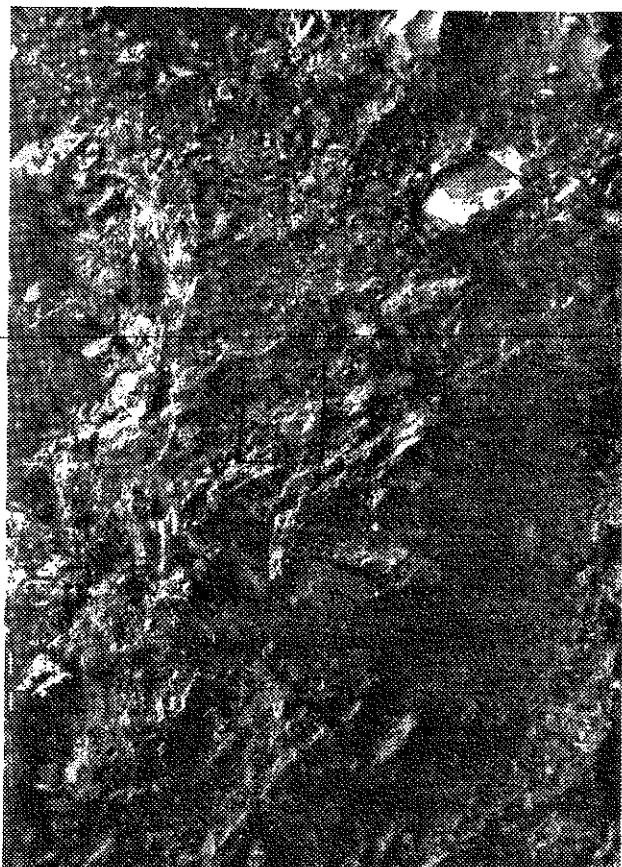
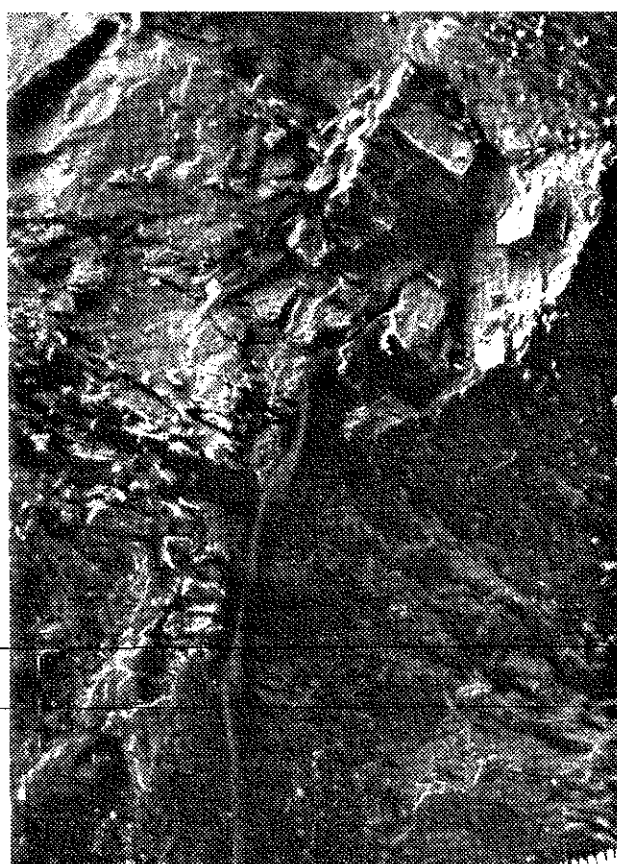


Specimen 2A, I 264, MP 16.2, WB, Left: 30X; Right: 300X



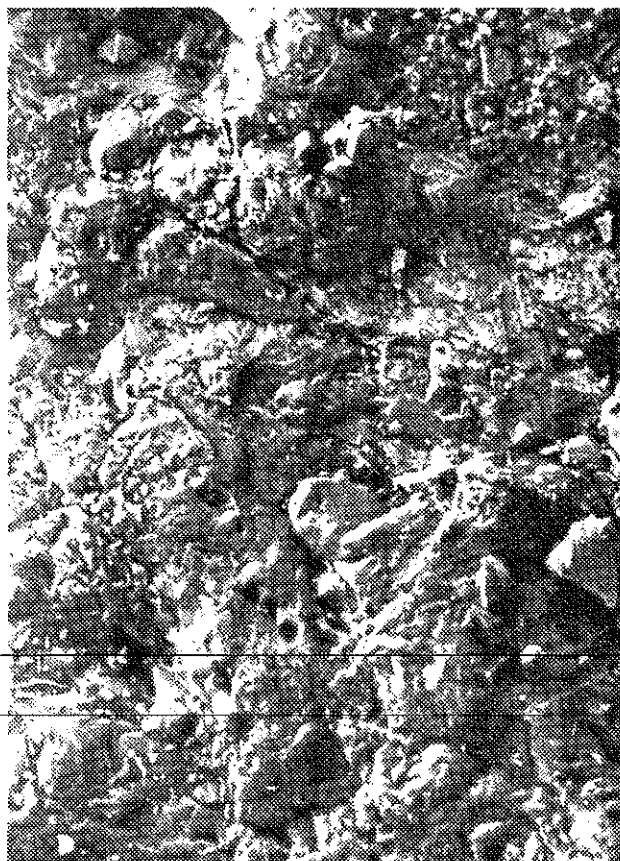


Specimen 3, I 264, MP 12.6, WB; Left: 30X; Right: 300X



Specimen 3A, I 264, MP 12.6, WB; Left: 30X; Right: 300X



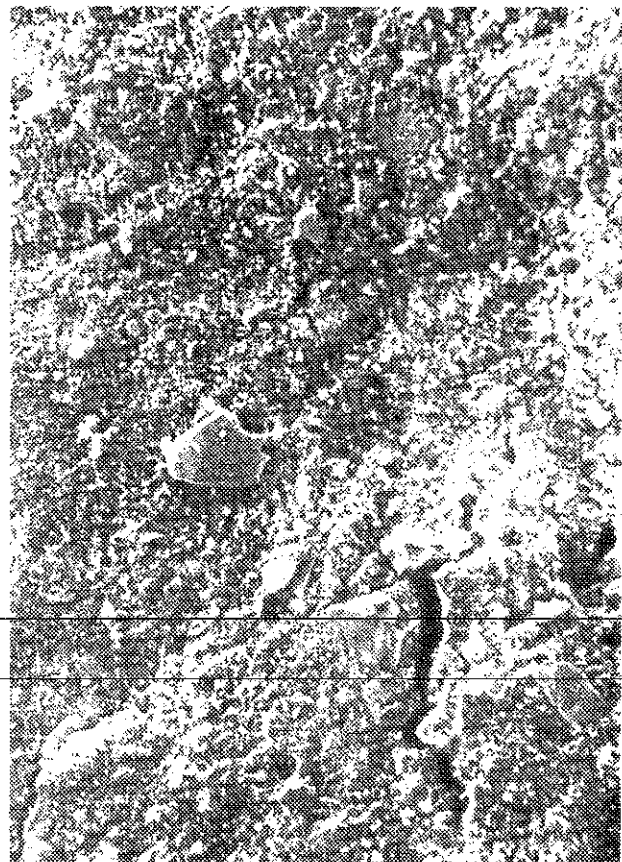


Specimen 5A, I 264, MP 9.8, EB, Left: 30X; Right: 300X



Specimen 6, I 264, MP 12.6, EB, Left: 30X; Right: 300X

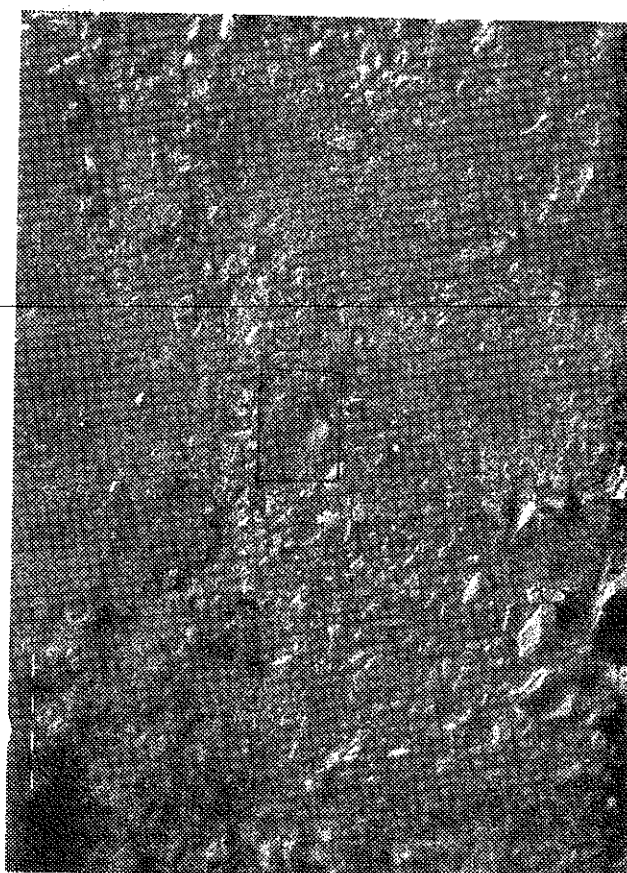




Specimen 9, Euclid Avenue, Lexington, WB; Left: 30X; Right: 300X

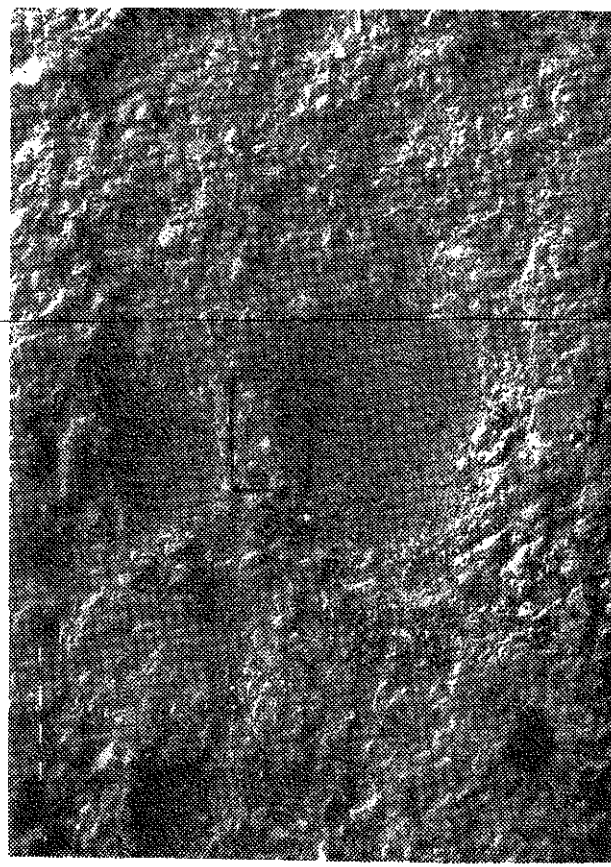
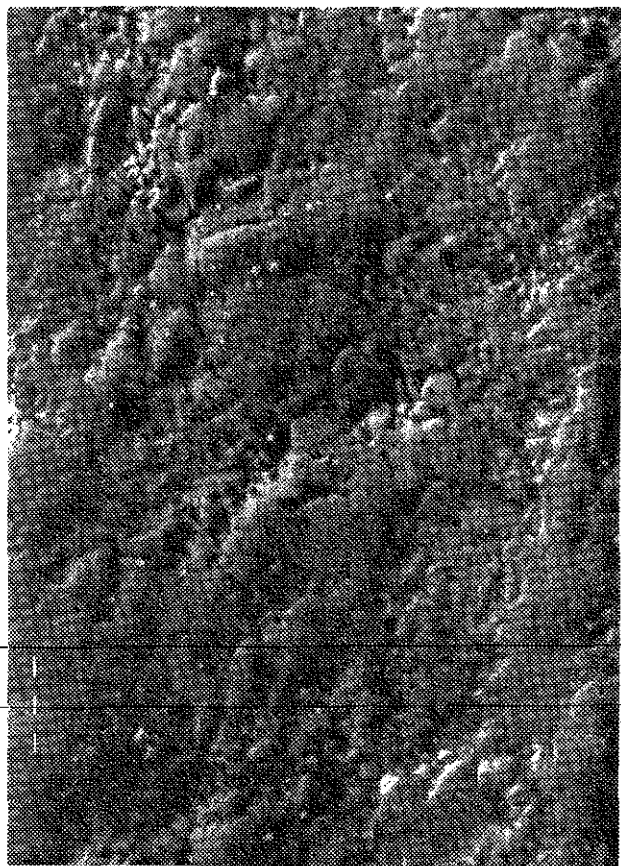


Specimen 10, KY 1974, Tates Creek Road, South of Cooper, Lexington; Left: 30X; Right: 300X



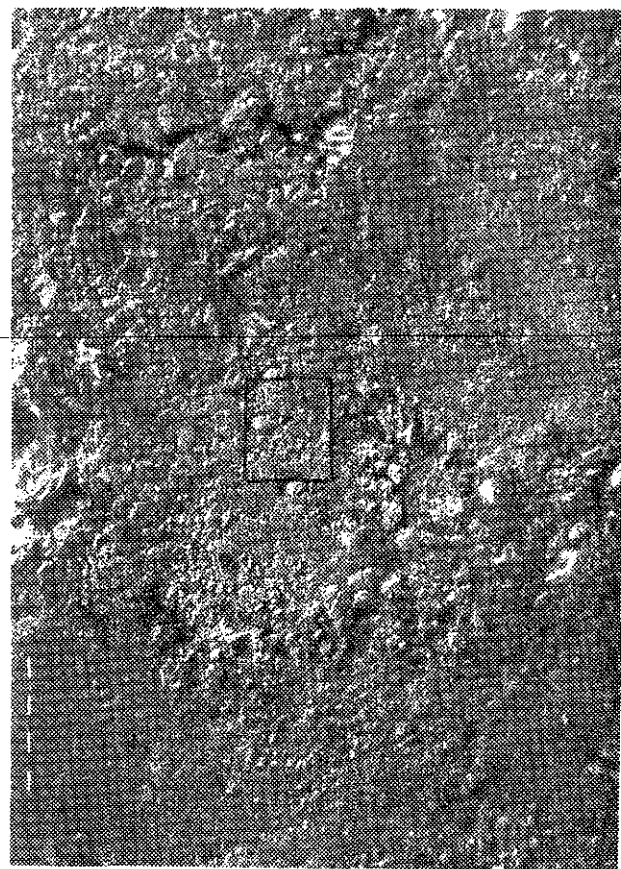


Specimen 13, I 64, MP 67.5, EB; Woodford County; Left: 30X; Right: 300X



Specimen 14, US 25, MP 14, SB; Madison County; Left: 30X; Right: 300X



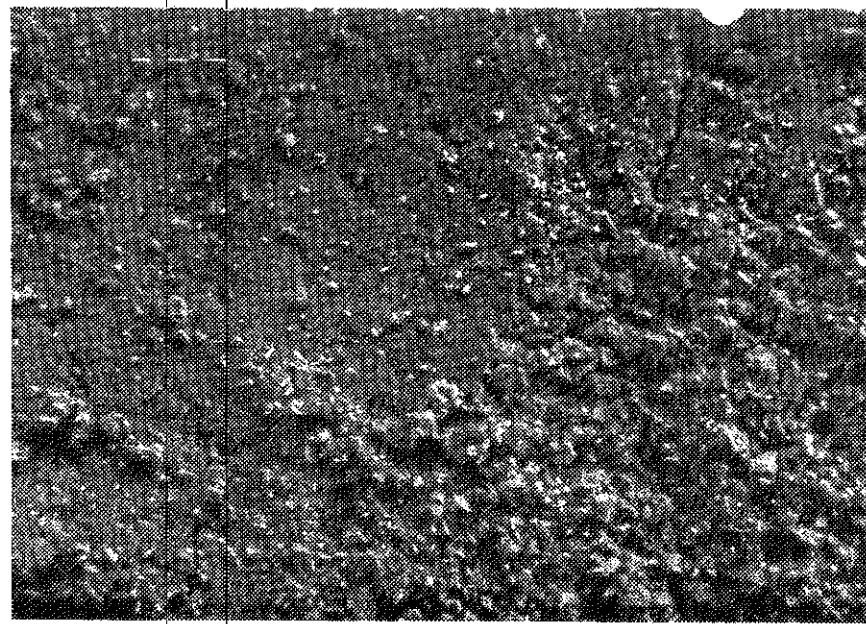
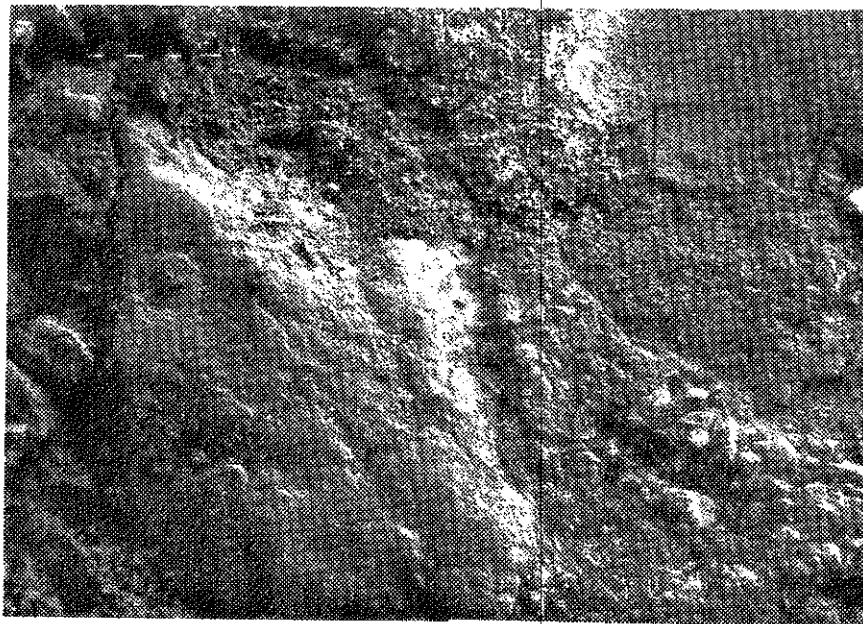


Specimen 17, US 27, MP 16, NB; Lincoln County, Left: 30X; Right: 300X

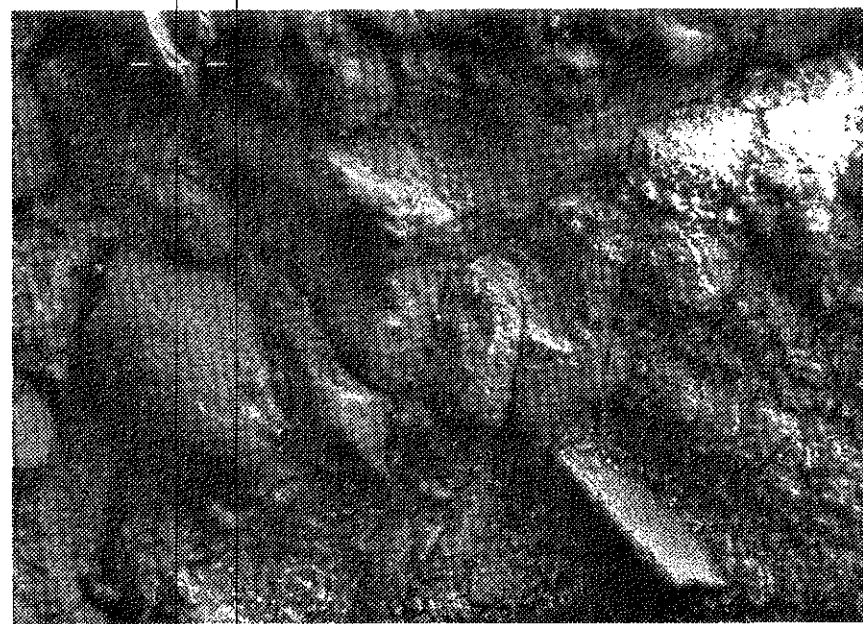
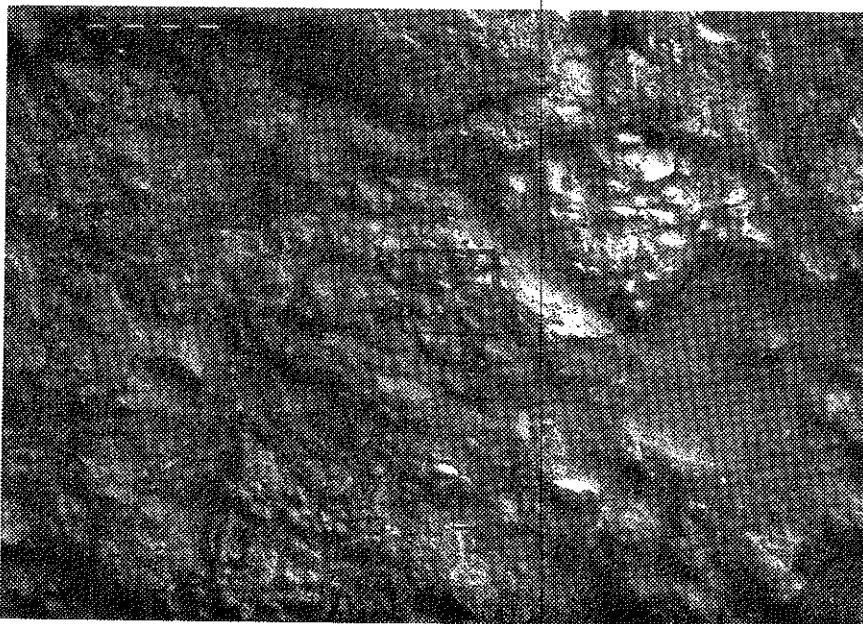


Specimen 18, US 68, MP 1; EB; Paris By-Pass, Left: 30X; Right: 300X

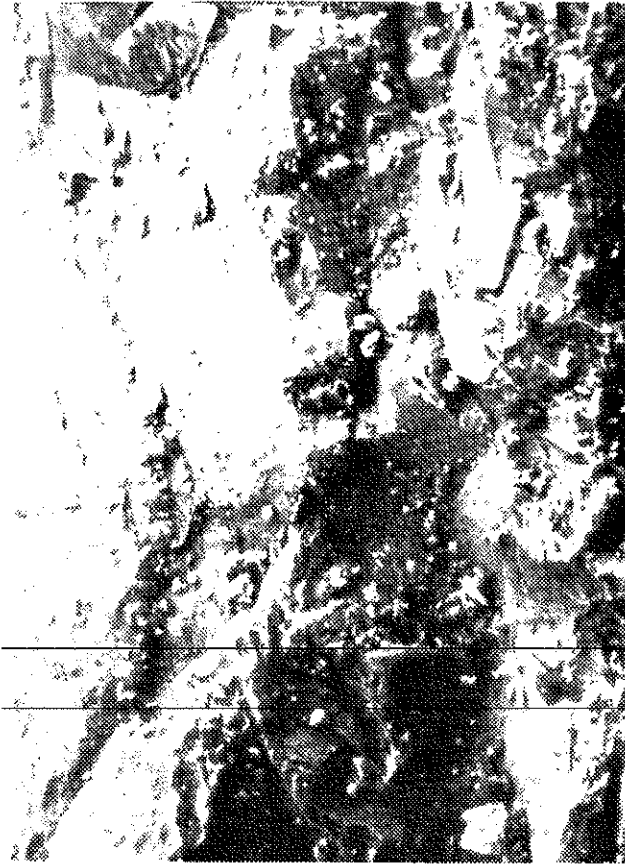




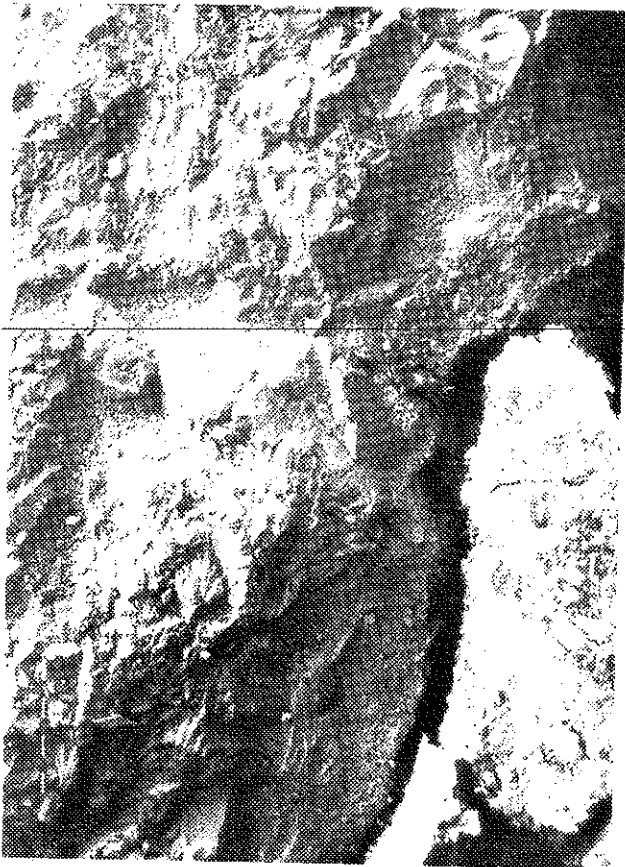
Specimen 21, US 60, MP 11.3, EB; Franklin County; Left: 30; Right: 300X



Specimen 22, Mt. Parkway, MP 57.5, EB; Wolfe-Magoffin Counties; Left: 30; Right: 300X

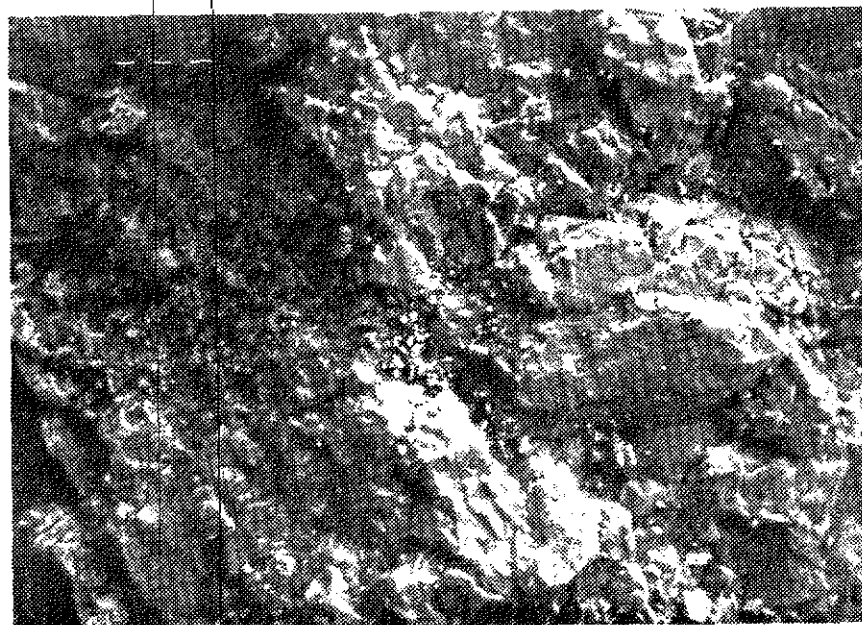
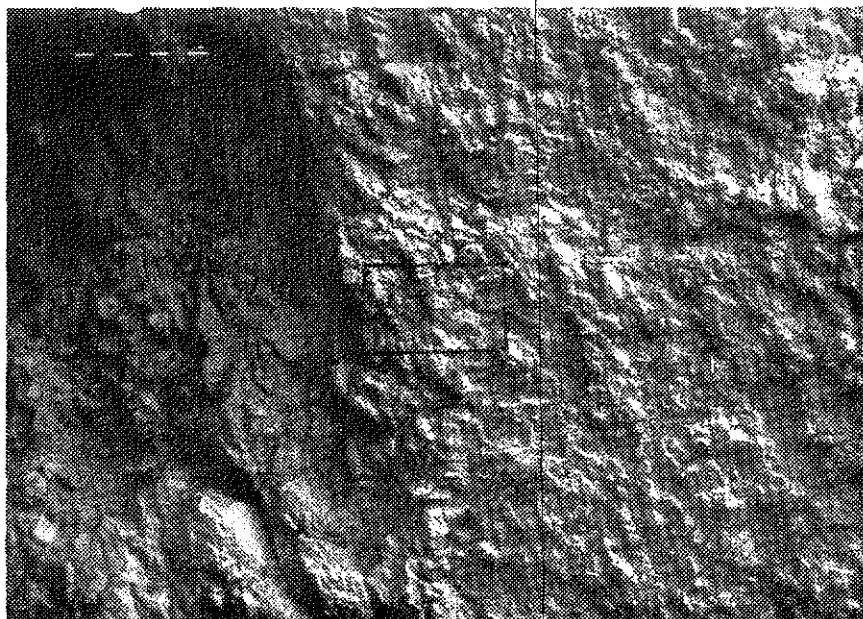


Specimen 25, KY 55, MP 9, SB, Taylor County; Left: 30X Right 300X

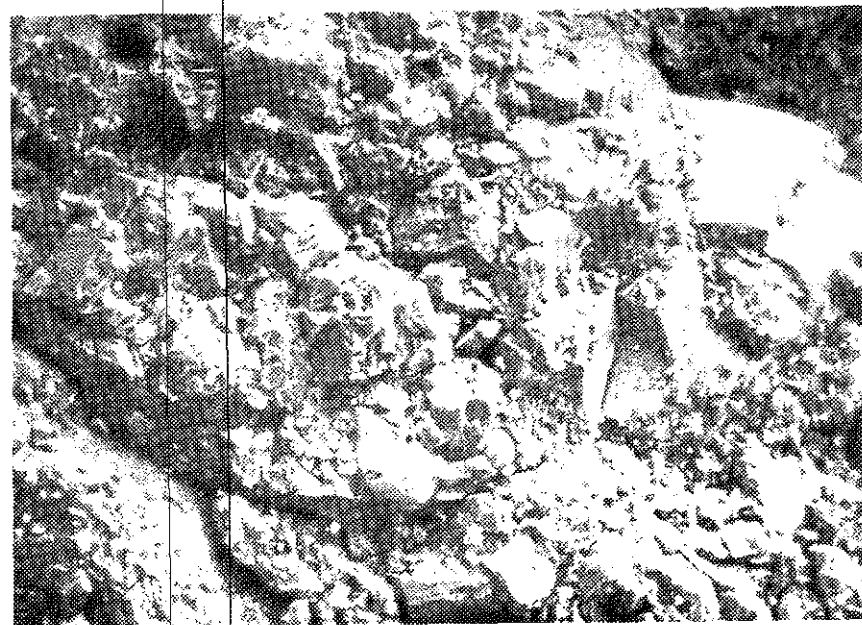
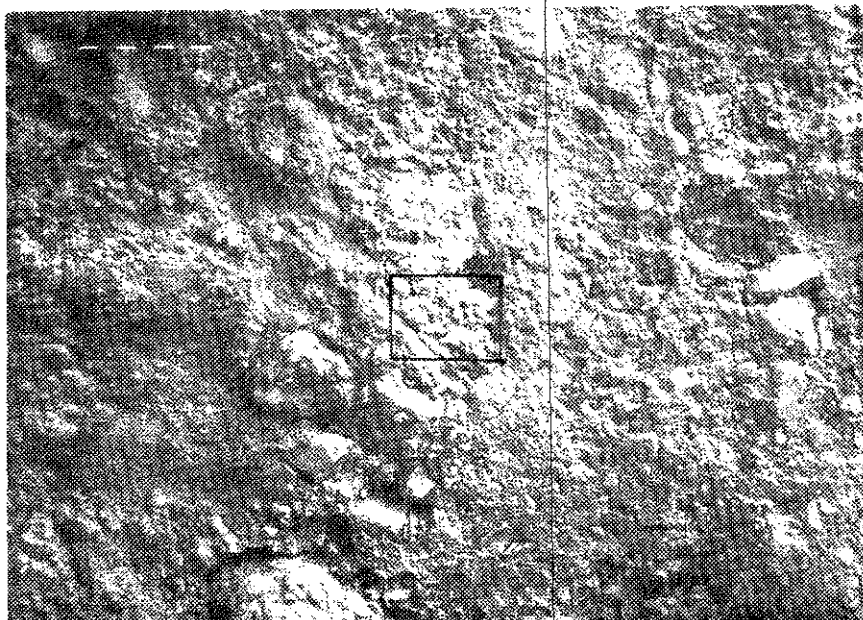


Specimen 26, US 31E, MP 20.1, SB, Nelson County; Left: 30X; Right: 300X

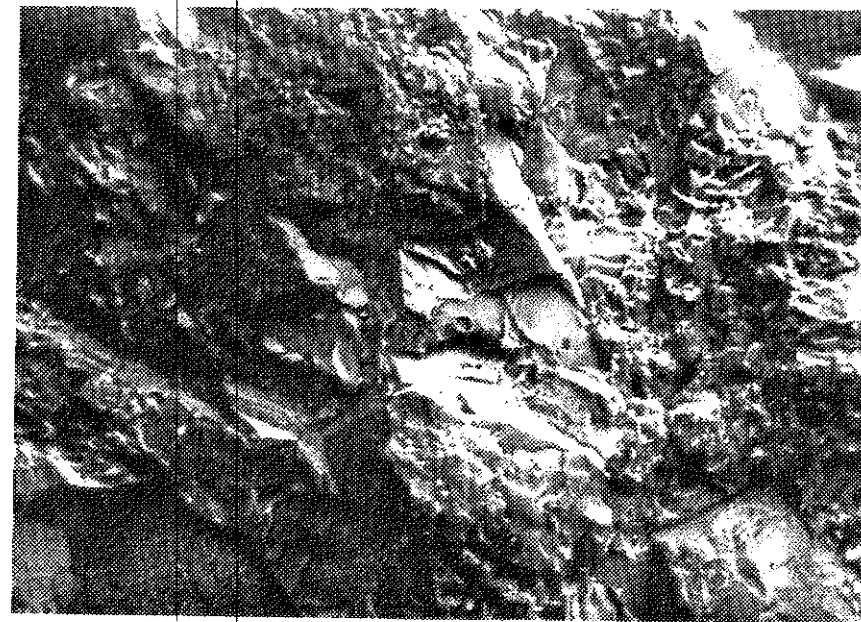
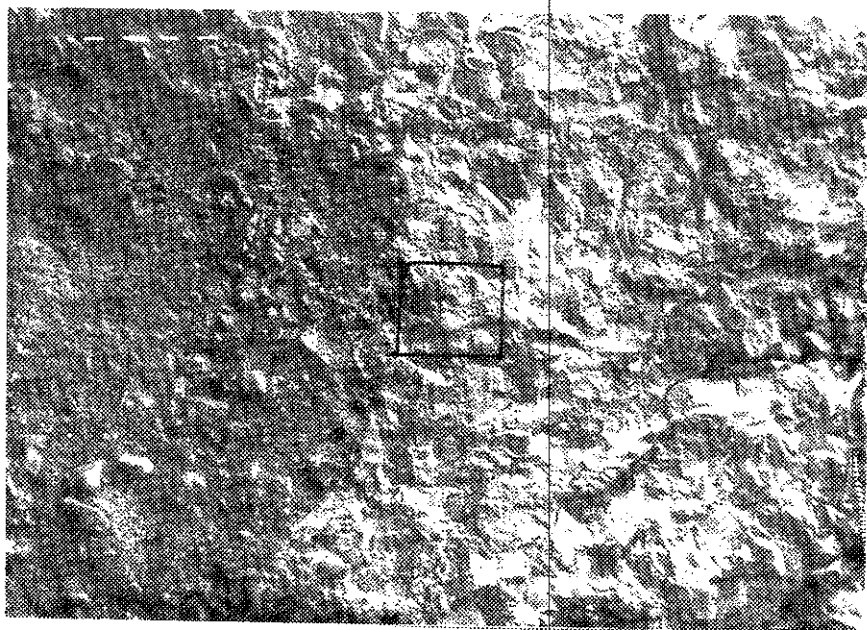




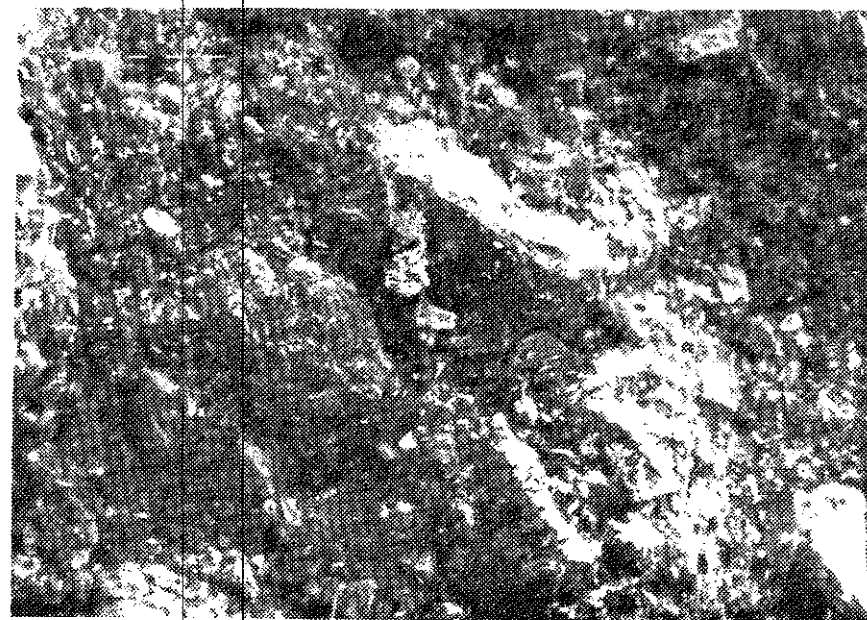
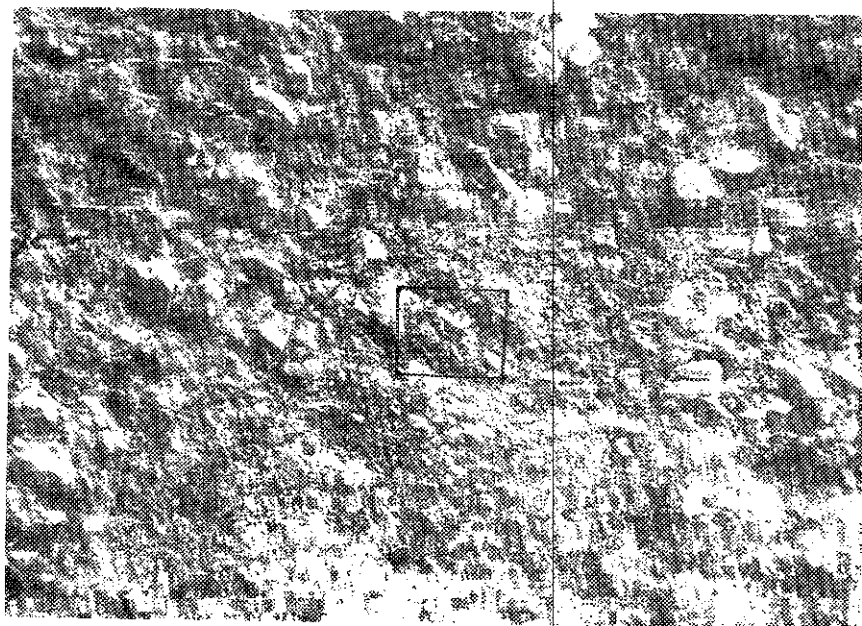
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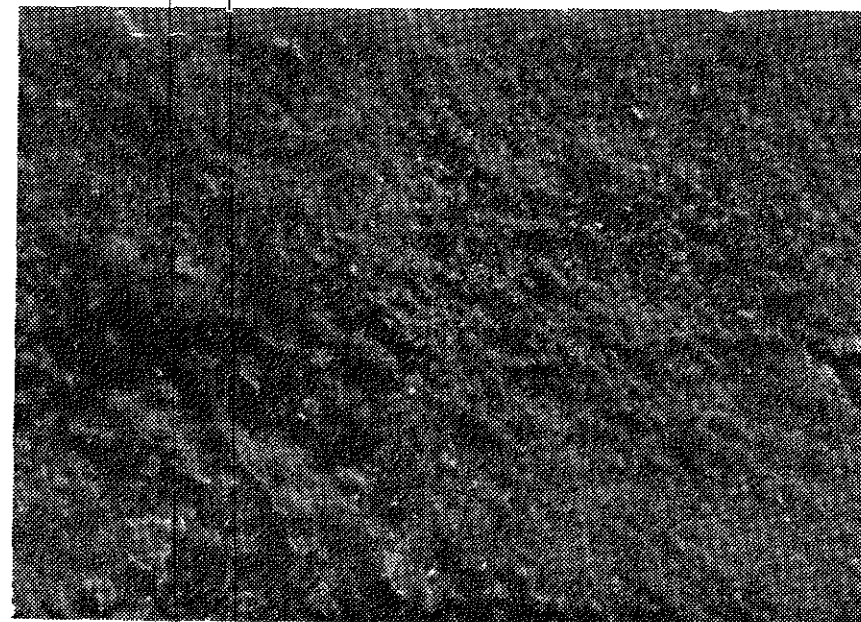
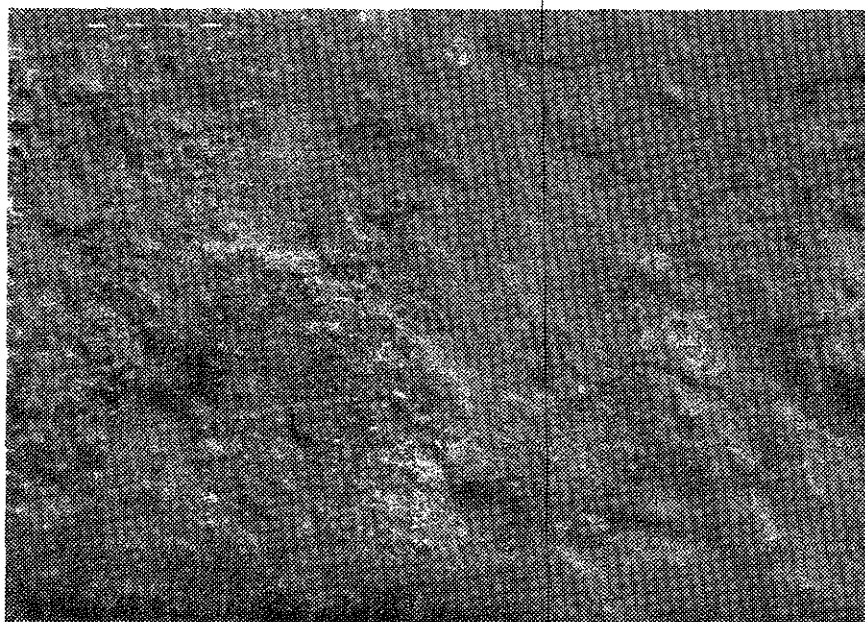
Specimen 30, US 31E, MP 19, SB; Nelson County; Left: 30X; Right: 300X



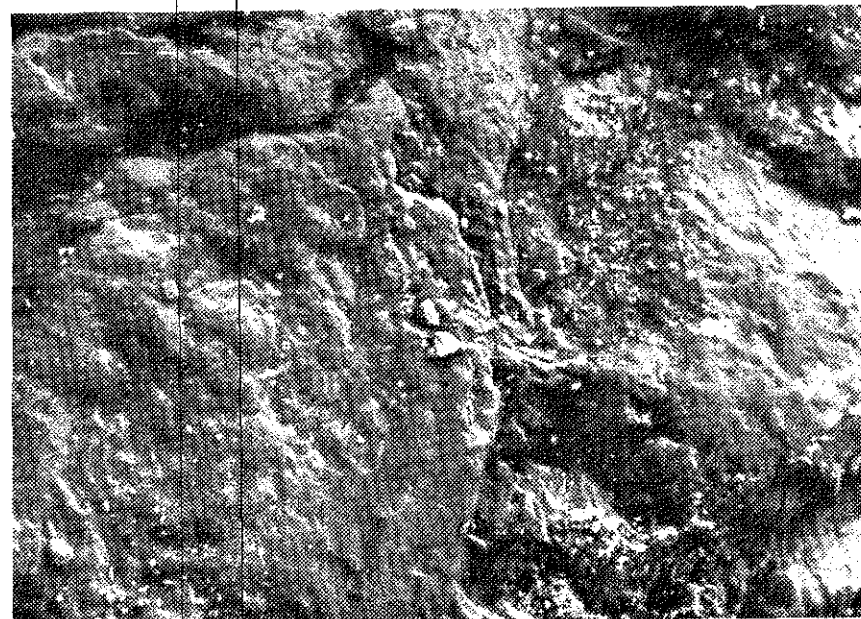
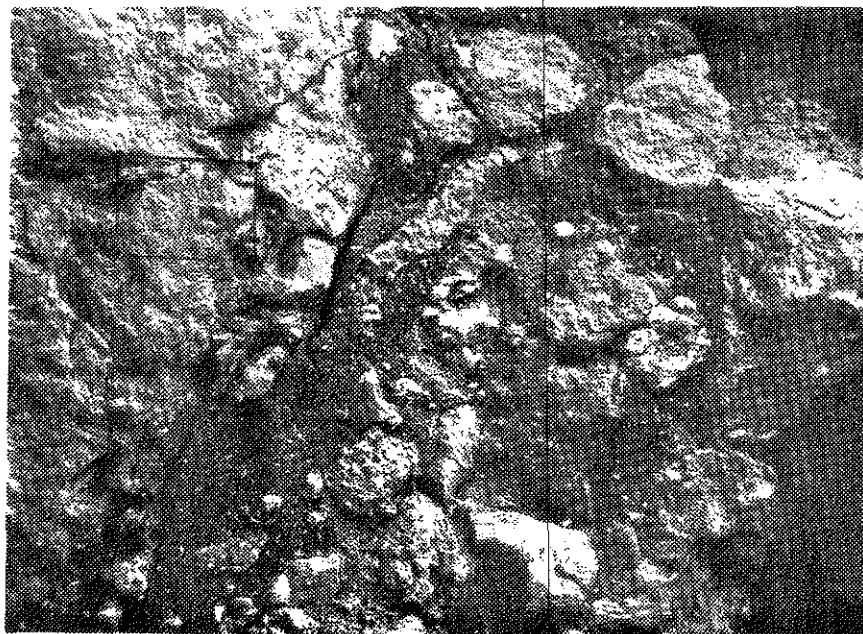
Specimen 33, KY 7, 0.7 mi to Henryville, EB; Perry County; Left: 30X; Right: 300X



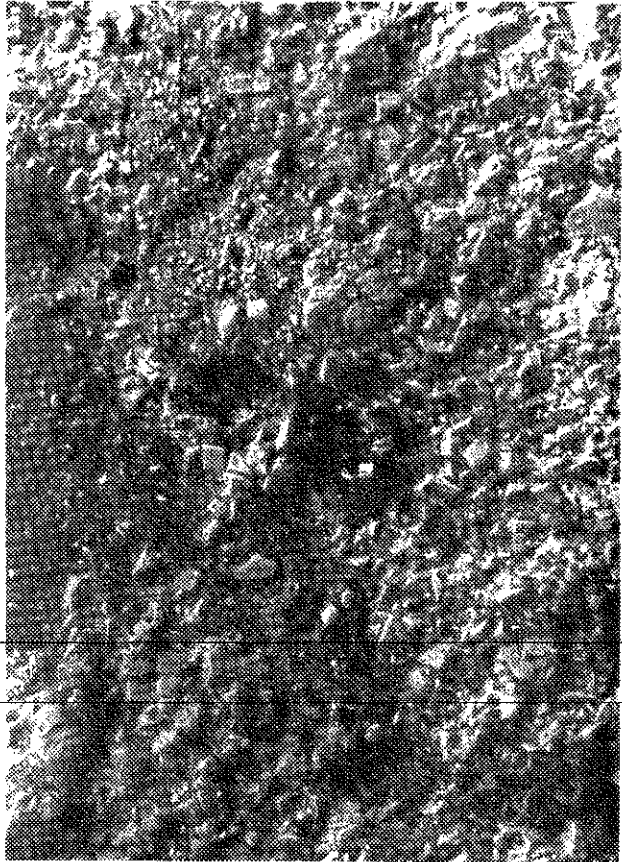
Specimen 34, KY 15, 2 mi to end of project, NB; Knott County; Left: 30X; Right: 300X



Specimen 37, US 62, MP 6.7, WB; Muhlenberg County; Left: 30X; Right: 300X



Specimen 38, I 24, MP 30, EB; Livingston County; Left: 30X; Right: 300X



Specimen 41, KY 94, MP 23.5, EB; Calloway County, Left: 30X; Right: 300X

